NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

AN INVESTIGATION INTO THE EFFECTS OF VERMICULITE ON NO_x REDUCTION AND ADDITIVES ON SOOTING AND EXHAUST INFRARED SIGNATURE FROM A GAS TURBINE COMBUSTOR

by

Kurt Richard Engel

September, 1990

Thesis Advisor: David W. Netzer

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An experimental investigation was conducted to determine the feasability of using catalytic reduction of NO_x emissions from a typical jet engine combustor in the test cell environment. A modified T-63 combustor in combination with an instrumented 21 foot augmentation tube containing a vermiculite catalyst was used. Several methods for containing the vermiculite were attempted. Both vermiculite and vermiculite which had been coated with thiourea were used. Up to 19% reduction in NO_x concentrations was obtained using the vermiculite coated with thiourea, however the pressure loss across the catalyst bed was measured to be 36 in. H_2O. The techniques used proved ineffective and unacceptable for gas turbine engine test cell applications. Tests were conducted using both Wynn's 15/590 and Catane TM (ferrocene) fuel supplements in order to determine their effectiveness for soot reduction and whether or not the exhaust plume could be changed. For the test

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An Investigation Into the Effects of
Vermiculite on NO_x Reduction and Additives
on Sooting and Exhaust Infrared Signature
from a Gas Turbine Combustor

by

Kurt R. Engel
Lieutenant Commander, United States Navy
B.S., U.S. Merchant Marine Academy

Submitted in partial fulfillment
of the requirements for the degree of

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Author: Kurt R. Engel

Kurt R. Engel

Approved by:

D.W. Netzer, Thesis Advisor

Raymond P. Shreeve

R.P. Shreeve, Second Reader

for E.R. Wood, Chairman
Department of Aeronautics and Astronautics

ABSTRACT

An experimental investigation was conducted to determine the feasibility of using catalytic reduction of NO_x emissions from a typical jet engine combustor in the test cell environment. A modified T-63 combustor in combination with an instrumented 21 foot augmentation tube containing a vermiculite catalyst was used. Several methods for containing the vermiculite were attempted. Both vermiculite and vermiculite which had been coated with thiourea were used. Up to 19% reduction in NO_x concentrations was obtained using the vermiculite coated with thiourea, however the pressure loss across the catalyst bed was measured to be 36 in. H_2O. The techniques used proved ineffective and unacceptable for gas turbine engine test cell applications. Tests were conducted using both Wynn's W-15\590 and Catane TM (ferrocene) fuel supplements in order to determine their effectiveness for soot reduction and whether or not the exhaust plume could be changed. For the test conditions utilized, the Wynn's additive was not effective in reducing the opacity of the exhaust plume, nor for reducing the exhaust plume temperature. The Catane TM reduced the opacity by 6.2%, but also had no significant effect on the plume IR signature.

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NOMENCLATURE

AR	Augmentation Ratio
cm	Centimeters
CO	Carbon monoxide
CO_2	Carbon dioxide
cSt	Centistokes
CH_4	Methane
D	Diameter
DACU	Data acquisition and control unit
EPA	Environmental Protection Agency
f	Fuel to air ratio
F	Fahrenheit
GPM	Gallons per minute
HP	Hewlett-Packard
IBP	Initial boiling point
$\dot{m}$	Mass flow rate
mV	Millivolts
NADEP	Naval Aviation Depot
NO	Nitric oxide
NO_x	Nitrogen oxides
NO_2	Nitrous oxide
NPS	Naval Postgraduate School
N_2	Nitrogen
O_3	Ozone

p	Pressure
ppm	Parts per million
psi	Pounds per square inch
R	Rankine
SCFH	Standard cubic foot per hour
SCR	Selective Catalytic Reduction
SO_x	Sulfur oxides
T	Temperature
UHC	Unburned hydrocarbons
V	Velocity

Subscripts/Superscripts

a	Air
aug	Upstream of catalyst in augmentor tube
avg	Average value across tube
bp	Bypass
c	Combustor
cx1	Upstream of quench air in combustor
cx2	Downstream of quench air in combustor
t	Stagnation or total
*	Nozzle throat conditions

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I. INTRODUCTION

Combustion-generated pollution of the environment from the operation of gas turbine engines comes in many forms. The large volumes of noxious gases and particulates generated by thousands of gas turbine engines worldwide can upset the environment if controls are not instituted.

The major sources of air pollution are listed below [Ref.1]:

- Soot or smoke from the carbon in the fuel that was unable to fully burn in the combustor.
- Unburned hydrocarbons (UHC) from incomplete combustion.
- Oxides of nitrogen (NO_x), a majority of which comes from nitrogen in the atmosphere in the presence of oxygen at high temperatures.
- Carbon monoxide (CO) resulting from incomplete combustion.
- Oxides of sulfur (SO_x) which come almost entirely from sulfur present in the fuel.

Soot or smoke is the most obvious pollutant and much effort has been made to control concentration and particulate size. CO and UHC levels are controlled when the engine is operated efficiently near stoichiometric limits. Unfortunately, as can be seen from Figure 1, this is also where the levels of smoke and NO_x increase [Ref.1].

Sulfur oxides are particularly damaging, not only to the environment but also to the engine. SO_x combines in the atmosphere to form sulfuric acid which is damaging to the environment and to internal engine parts. However, it is possible to remove the sulfur in the refining process and MILSPEC's require less than 0.1 % sulfur by mass in jet fuel to control the effects of sulfur. Because of these efforts SO_x pollution from gas turbines is minimal.

Soot size and concentration has been studied extensively at the Naval Postgraduate School [Refs. 2 and 3] and by Cashdollar [Ref. 4].

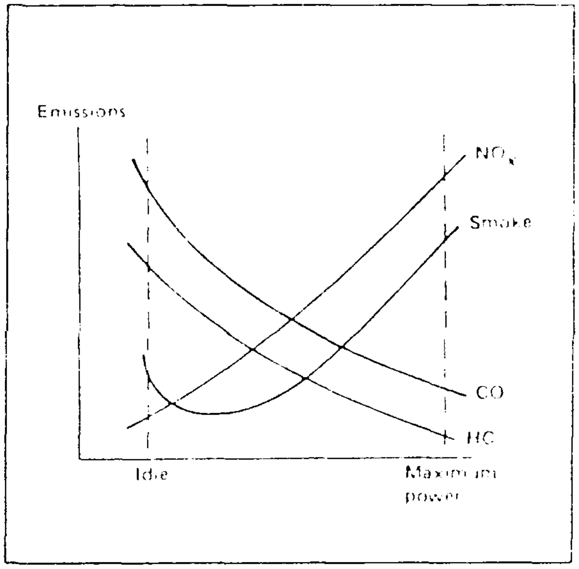


Figure 1 Emissions Characteristics of Gas Turbine Engines

The Environmental Protection Agency has written goals for commercial engine manufacturers concerning emissions and these goals have been generally met. Military engines are exempt from these requirements when operated on an aircraft. However, it has been determined that engines operated in a test cell are subject to the emissions regulations applicable to a stationary gas turbine power plant. A typical Naval Aviation Depot (NADEP) runs an engine for five to six hours before it is approved for use in an aircraft.

In Northern California, the Bay Area Air Quality Management District closely monitors emissions from fixed sources in its jurisdiction. NO_x emissions are limited to 150 lbs/day for existing sources and new sources are limited to 10 ppm. Sooting limits are any concentration exceeding one on the Ringleman scale for greater than 30 minutes. There is a wide variety of additives available on the market. At this time the U.S. Navy at NADEP Alameda uses Cerium Hex Cem soot supressing additive when testing the T-56 engine. At the United Airlines test cells at San Francisco International Airport, DTG-2, a barium based chemical, is used to control the sooting of turbojet engines. These metal based additives are usually effective in controlling the soot but there are draw backs:

- They tend to form deposits in the engines, consequently their use is time limited.
- They are aggressive chemicals that can cause damage to the seals in the engine.
- Some additives (in particular barium and manganese based) are toxic and may have long term effects worse than the soot itself. [Ref. 1 and 5]

For these reasons it is hoped that an inexpensive additive can be found that does not contain metal and will reduce sooting. Wynn's W-15/590 claims to be one such product. In addition to soot reduction, the additives can increase the combustion efficiency in some types of engines. The effects of these additives on the exhaust IR signature is unknown.

NO_x is produced to a certain extent in all combustion that reaches at least 3200 R. It is largely independent of the fuel and solely dependent on the flame temperature in the primary zone. The production is by the following reactions at a very fast rate [Ref. 6]:

$$O + N_2 \rightleftharpoons NO + O$$

and

$$N + O_2 \rightleftharpoons NO + O$$

The source of the nitrogen is the atmosphere and can not be controlled. Therefore, the only way to reduce the NO_x is to change the combustion temperature with staged burning or water injection [Ref. 6], or treat the entire exhaust flow with a scrubber or absorber system [Ref. 7].

A scrubber system would not be the best choice for a treatment system because of the complexity of required plumbing. It was discovered in a U.S. Air Force funded study that in laboratory conditions it is possible to remove up to 96% of the NO_x from a combustion stream using the catalytic and adsorbing properties of vermiculite [Ref. 8].

Vermiculite is an inexpensive silicate with the formula $Mg_3Si_4O_{10}(OH)_2 * xH_2O$. It is related to mica and talc and has the unique property of expanding upon heating up to 30 times original volume. It is non-toxic and frequently used in potting soil and as an insulator in the building industry [Ref. 9]. Its catalytic properti^ are not well understood.

Catalytic reduction of NO_x is a much studied problem in industry. Typically commercial Selective Catalyst Reduction (SCR) beds are constructed of precious metals or natural and manmade zeolites. Mobil Oil Corp. makes one such catalyst ZSM-5 [Ref. 10]. These SCR's require ammonia injection in the ratio of one-to-one on a molal basis with NO_x. When combined with combustion chamber water injection these SCR beds are able to achieve 85% reduction in exhaust flow NO_x concentration.

While this installation works well for steady state commercial operations, it is not believed the precise control of ammonia injection would be possible with the rapid throttle movements necessary in engine test. If too little ammonia is injected the NO_x is not reduced and if too much ammonia is injected it passes through the SCR unused and is called "slip". In addition, the efficiency of the reduction of NO_x with ammonia in a SCR is very temperature dependent. Typically the SCR bed must be maintained at a constant 700 deg. F.

The following goals were set as achievable within the time available for the present investigation:

- Acquire vermiculite catalyst and chemicals that seemed likely to produce the best results in typical engine test cells.

- Redesign the catalyst containment to eliminate the large pressure drop associated with the existing design.

- Measure the effectiveness of various catalyst bed depths and chemical coatings on reduction of NO_x and CO.

- Compare the effectiveness of Wynn's W-15/590 additive to Catane TM (ferrocene) for soot emission reduction.

- Evaluate the effects of W-15/590 and Catane TM (ferrocene) on the exhaust plume thermal distribution.

II. EXPERIMENTAL APPARATUS

A. COMBUSTOR

The production of combustion gases was accomplished using an Allison T-63-A-5A gas turbine combustion chamber as modified by Grafton [Ref. 11]. The modifications included the addition of a quench manifold to simulate the temperature drop resulting from work extraction of the gas producer turbine and the power turbine. In contrast to Behrens [Ref. 12] investigation, during the NO_x portion of this research the quench was not used. This was done to prolong the high temperatures of the primary zone and boost the production of NO_x.

The quench was used in the soot studies to help quench the soot formed, and prevent its combustion. The quench air was supplied from the main air line through a sonic choke (D_{cr} = 0.242 in.) sized to provide 0.5 lbm/sec flow with a minimum pressure of 475 psi from the main air line.

Prior to initial runs all connections were checked for security, and filters and ignitors were cleaned. Optical windows were cleaned prior to each run. A gas bottle of nitrogen was connected to a portion of the existing purge piping to flow across the windows and ensure they did not obscure with soot. Table I is a list of operating parameters for the T-63 at sea level standard conditions.

TABLE I T-63 OPERATING SPECIFICATIONS [Ref. 13]

Rating	f	$\dot{m}_{air}$	$\dot{m}_{fuel}$	T_t
		lb/sec	lb/sec	deg F
Takeoff	0.019	3.17	0.061	1380
Military	0.017	3.04	0.053	1280
90%	0.017	2.95	0.049	1226
75%	0.015	2.82	0.043	1148

Note: compressor pressure ratio= 6.25, Pc=92 psi, engine length= 40.4 in, width= 19.0 in, weight= 138.7 lbs. height= 22.5 in. Military power limited to 30 min.

B. AIR SUPPLY

Compressed air to run the combustion chamber was supplied by a bank of air tanks pressurized to 3000 PSI (Figure 2). These tanks were filled between runs by compressors with an air dryer. The air supply could operate the T-63 combustor at the Military power level for approximately 7 minutes.

A pneumatically powered, dome loaded pressure regulator was operated from the control room to regulate the air pressure through the sonic chokes. The temperatures and pressures were read by the HP computer system and used to

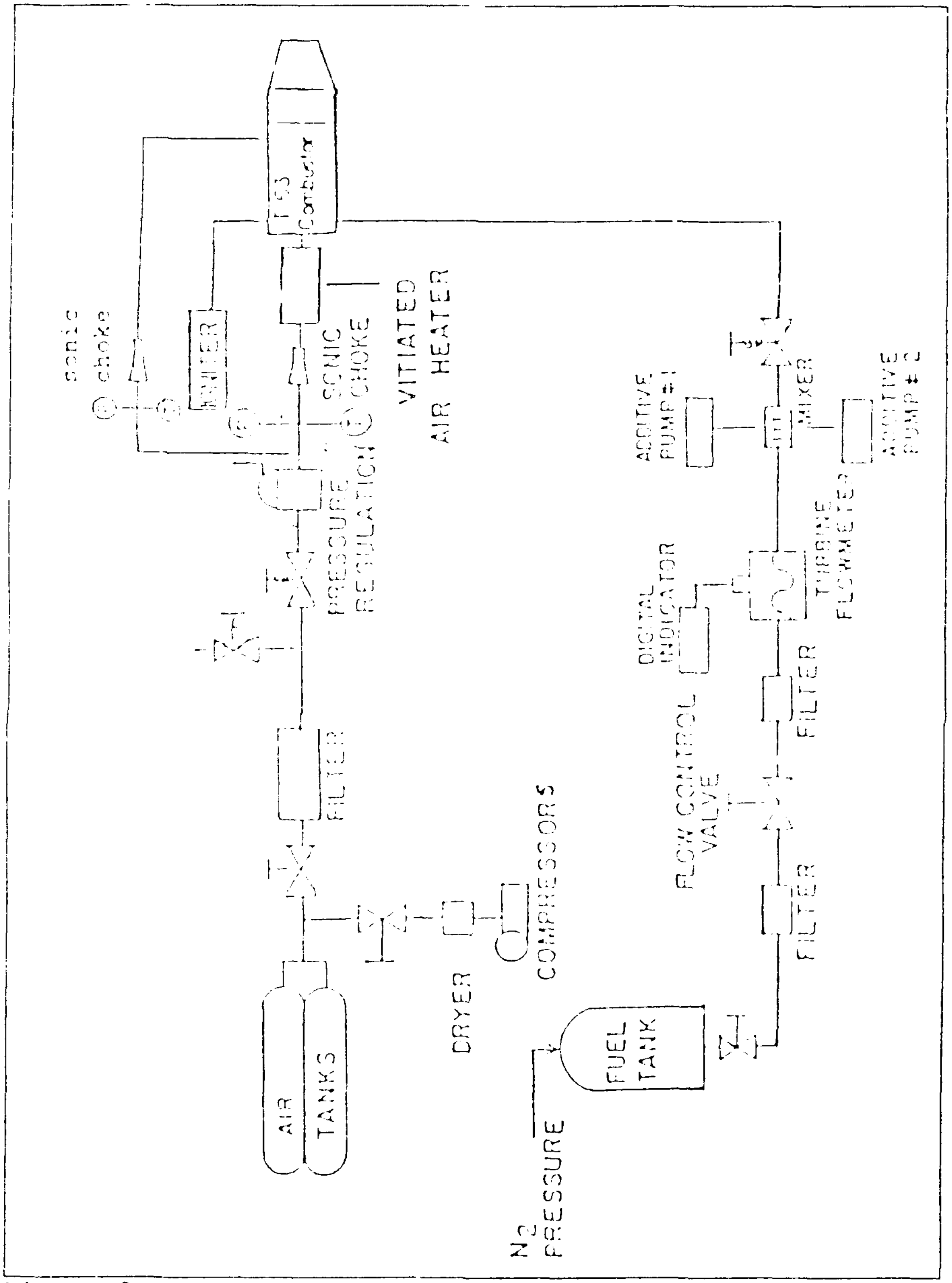


Figure 2 Schematic of Air and Fuel Supply [Ref. 3]

compute the air mass flow rate.

C. FUEL SUPPLY

Metered fuel was supplied to the combustion chamber through the fuel atomizer in the top of the chamber (Figure 2). The 20 gallon fuel tank was pressurized with nitrogen and the flow rate was controlled using a throttle valve in the control room. The turbine flowmeter signal, in gallons per minute (GPM), was read in the control room at a digital display and also recorded by the data acquisition system. The properties of the fuels employed are listed in Table II. The fuel additives were injected into the fuel line in a mixing chamber at the specified concentration via two Eldex additive pumps. These pumps were operated from the control room and allowed isolation of the effects of the additive.

TABLE II PROPERTIES OF FUELS [Ref. 3]

Properties of Fuel	NAPC 3	NAPC 4
API Gravity @ 15 deg C	41.3	41.6
Distillation IBP deg C	171	180
Temperature recovered 10% deg C	192	202
Temperature recovered 20% deg C	203	210
Temperature recovered 50% deg C	227	228
Temperature recovered 90% deg C	261	264
End Point deg C	276	282
Residue ml	1.4	1.4
Loss ml	0.1	0.5
Composition Aromatics vol%, max	22.8	18.6

Properties of Fuel	NAPC 3	NAPC 4
Olefins vol%	0.75	0.79
Hydrogen content wt%	13.66	13.82
Smoke Point mm	20.0	21.0
Aniline-Gravity Prod.	5811	6140
Freeze Point	-34.0	-34.5
Temperature @ 12 cSt deg C	-35.6	-31.7
Viscosity @ 37.8 deg C cSt	1.62	1.74

D. TEMPERATURE AND PRESSURE RECORDING

Nine thermocouples and four pressure transducers were read by the Hewlett-Packard (HP) 3054A Data Acquisition/Control Unit (DACU). The computer read the data and made calculations for output during hot runs. All thermocouples were Chromel-Alumel (Type K) and the computer was programmed to convert analog readings to temperatures for printout. Table III provides the acquisition channel numbers and parameters measured:

TABLE III DATA ACQUISITION CHANNEL KEY

Parameter	DACU Chan No.
P_a main air pressure	24
P[illegible] combustion chamber pressure	23
P[illegible] heater fuel pressure	22
P[illegible] heater make up oxygen	21
T_a main air temperature	60

Parameter	DACU Chan No.
T_{air} combustor air inlet	61
T_{ex1} combustor exhaust upstream quench	62
T_{ex2} combustor exhaust downstream quench	63
T_{ho} heater make-up oxygen	64
T_{hf} heater fuel temperature	65
T_{augup} augmentor temp upstream	66
T_{augd1} augmentor temp downstream	67
T_{augd2} augmentor temp downstream	68

E. AUGMENTOR TUBE

The steel augmentor tube as described by Behrens [Ref. 12] was used for preliminary runs. It was then modified to the configuration shown in Figures 3 and 4. The vertical portion of the augmentor tube was divided with stainless steel mesh into different bed screen spacings and partially filled with vermiculite. This method was chosen to eliminate to the maximum extent possible the pressure loss due to the vermiculite in the exhaust flow. The catalyst basket used by Behrens [Ref. 12] was split in half and formed the top and bottom of a variable distance fluidized bed in the exhaust flow for the vermiculite. Inside the augmentor tube a deflector plate was installed at 45 deg. at the tube bend to help turn the flow. The deflector plate was sized so that it did not restrict the tube cross section.

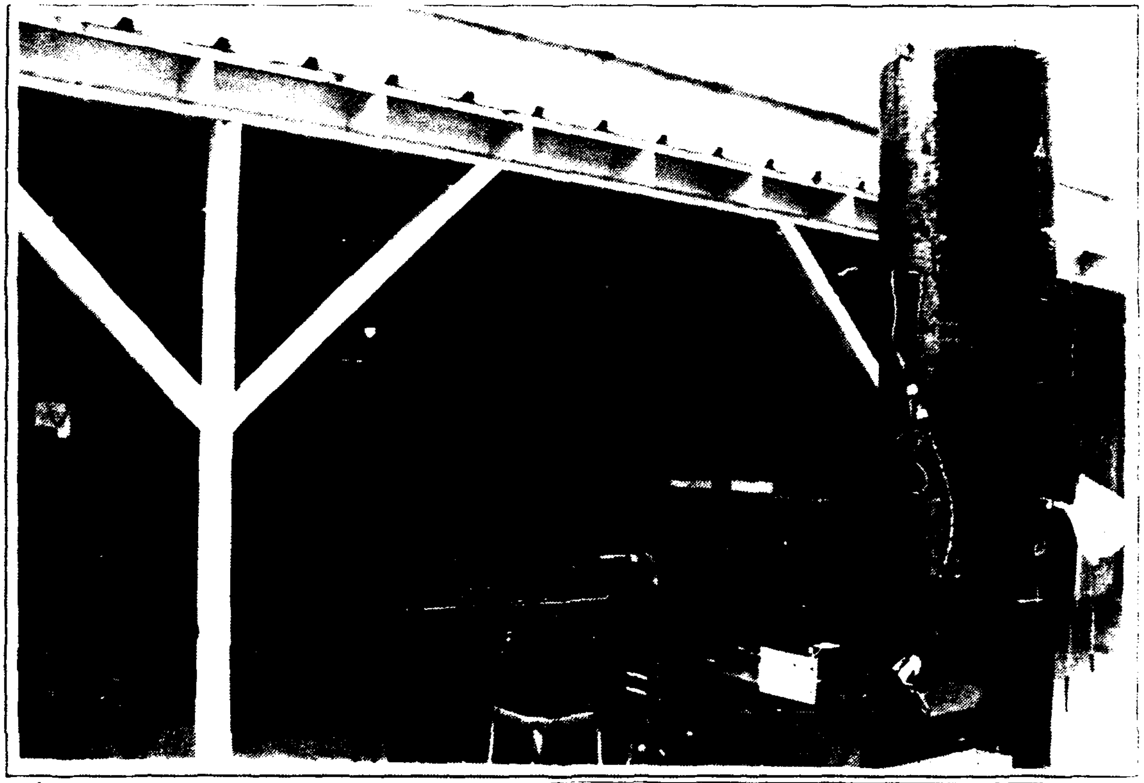


Figure 3 Photograph of Augmentor Tube

A blocking plate was attached to the front of the augmentor tube. The opening of the plate could be adjusted to regulate the amount of augmentation air entrained with the engine exhaust, and thereby change the augmentation ratio (Figure 5). In these experiments the five inch diameter opening was not varied.

Determination of the total mass flow through the augmentor tube was made by measuring the velocity profile and gas temperature. A motor driven traversing pitot-static system (Figure 6) was mounted 24 inches upstream of the turning baffle. A slant tube manometer was used to record P.-P across the tube diameter.

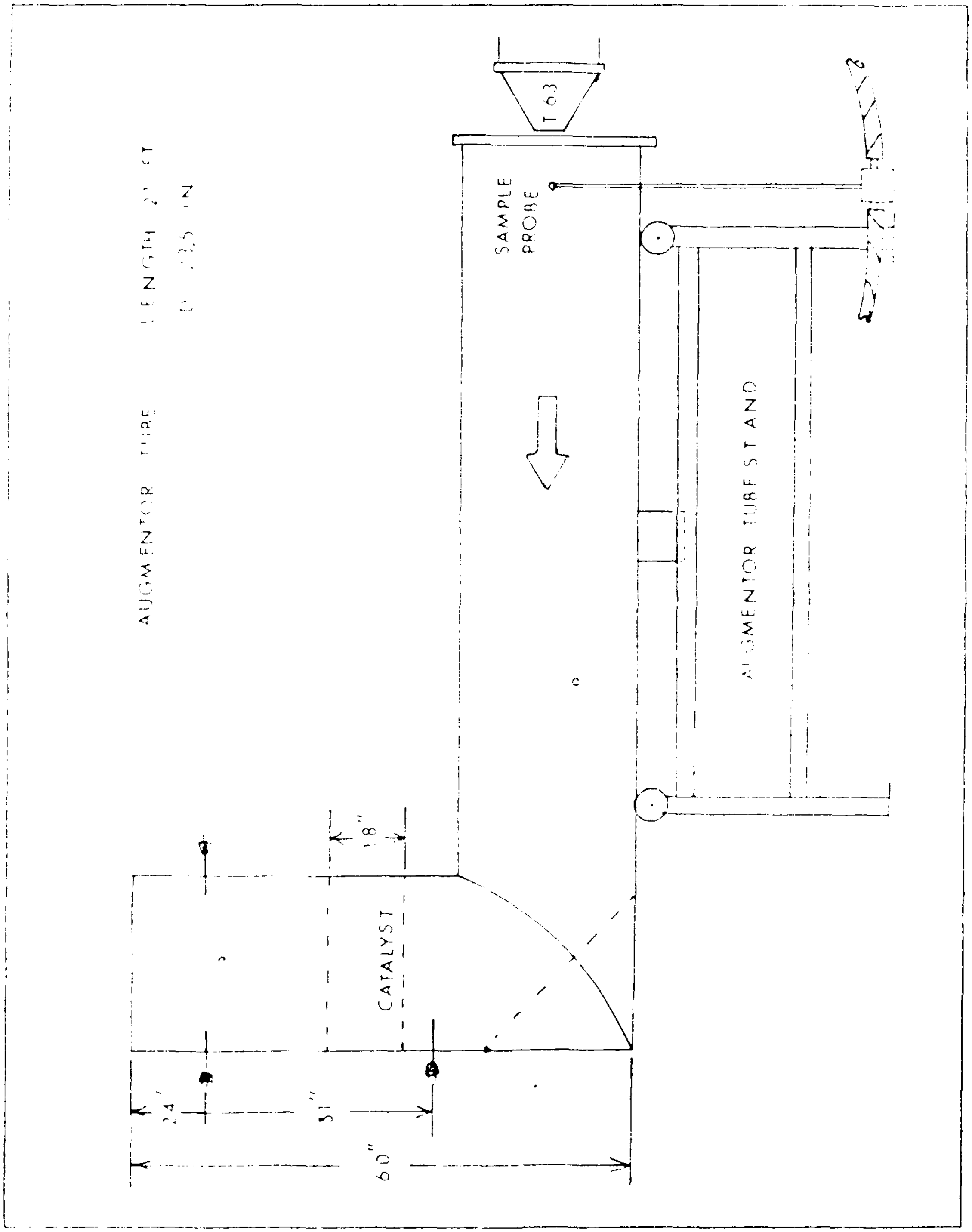


Figure 4 Schematic of Augmentor Tube and Instrumentation

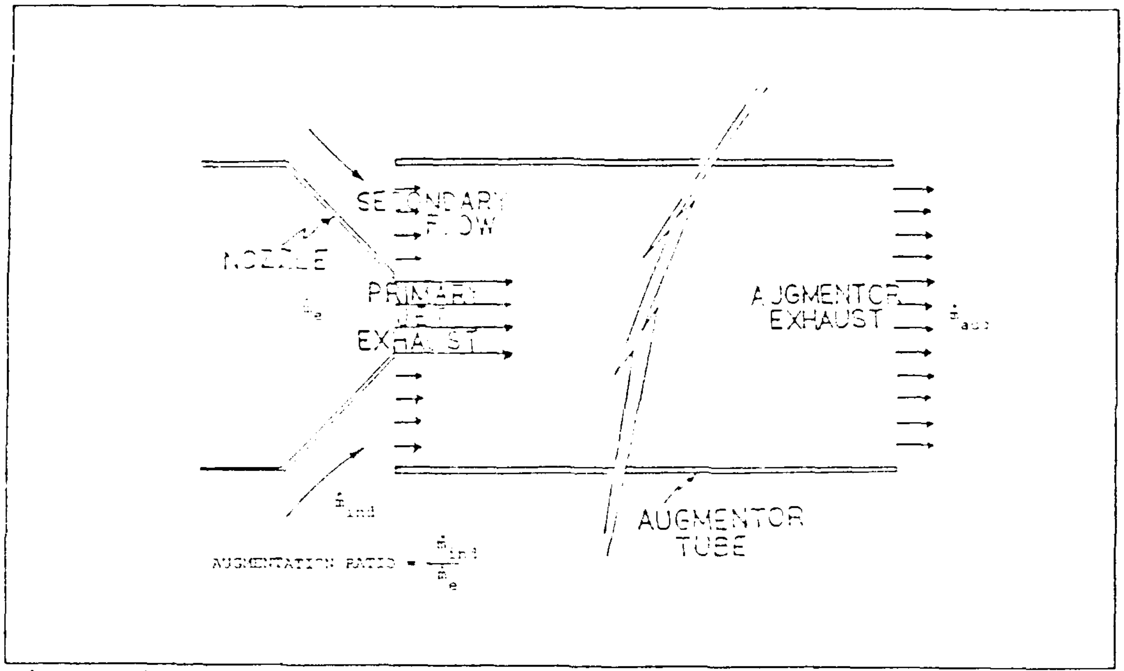


Figure 5 Determination of Augmentation Ratio

F. OPTICS

The transmittance measurements were made with a single laser through the combustion chamber to a photodiode target. Transmittance was measured at several locations through the exhaust stream. It was decided to use the forward most optical ports with purge tubing in the aft combustor can since it offered the most observable transmittance measurements. The diode output signal was amplified and recorded on a strip chart recorder in the control room. The source was a 0.6328 micron helium-neon laser operating at 8mW. A 50% narrow band pass filter was used to reduce the adverse effects of ambient light.

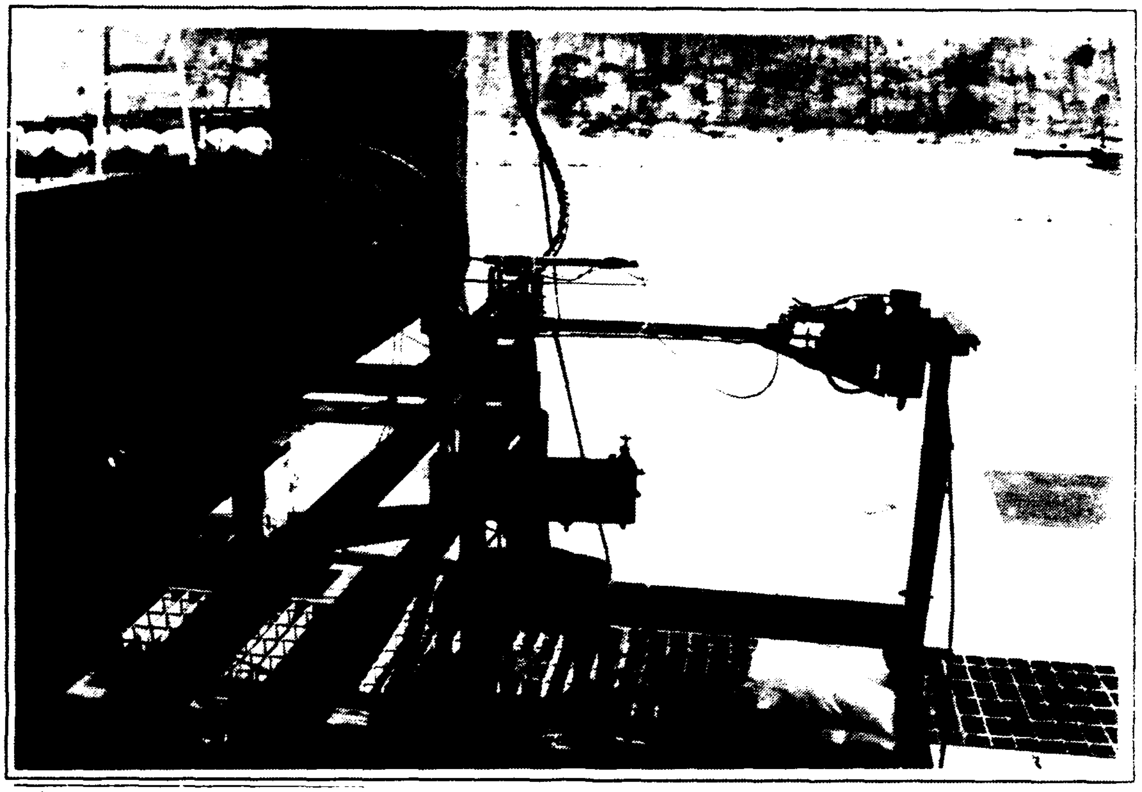


Figure 6 Photograph of Pitot-Static Traverse

G. INFRARED MEASUREMENT EQUIPMENT

Infrared measurements of the gas temperatures were made using an Agema real time thermal imaging system. The scanner was equipped with a 20 deg field of view lens and three filter settings for use in different thermal ranges (Figure 7). The surface of the object was scanned 25 times per second, producing a TV-like image. The detector was thermo-electrically cooled and a built-in black body source provided a reference for self calibration. The scanner operated in the short wavelength band (SWB) of the middle IR spectrum between two and 5.6 microns wavelength. The picture produced had 280 lines per frame with 100 elements/line. Temperature accuracy was better than $\pm$ 2° C. The Noise Equivalent Temperature Difference was 0.1° C at 30° C.

Figure 7 Photograph of IR Scanner

Scanner images were processed by a dedicated Compaq 286 PC with CATS E software and hardware. The software gave the standard 40 Mb hard disk the capability to store 930 IR images. These images could be either single shots, rapid sequences or integrations over a period of time. The software offered many features for post run analysis. These included: subtraction of one image from another, magnification, relief, and an auto scaling feature. Complicated keystroke sequences could be stored in macro programs to be run during the short test runs. Correct temperature display required knowledge of the emissivity of the object viewed. The CATS E software offered calculation of the emissivity of complex emissivity distribution s~enes.

H. GAS ANALYSIS EQUIPMENT

Gas samples were taken both upstream and downstream of the catalyst to determine its effectiveness. The upstream sample was taken from the c· er of the augmentor tube eight inches downstream from the opening. This location precluded any ambient air from diluting the sample. The downstream sample location was taken 12 inches above the top catalyst screen. A three-way solenoid valve operated from the control room allowed choice of sample location.

The sample line heater mentioned in Behrens [Ref. 12] malfunctioned d ing early runs. It was determined by testing that the NO_x readings were not affected.

1. Model 900 Heated Sample Gas Dilution Unit

Sample gas was drawn by vacuum pumps into the Thermo Environmental Model 900 at 1.3 SCFH, and mixed with dilution air at a 2 1 ratio. The sample was heated and filtered and then sent to the Model 10AR and Model 48 [Ref. 14]. Figure 8 is a schematic for the sample flow path.

2. Model 10AR NO/NOX Analyzer

The conditioned and diluted sample was fed through teflon tubing to the Thermo Environmental Model 10AR NO/NO_x Gas Analyzer. The Model 10AR was capable of continuous

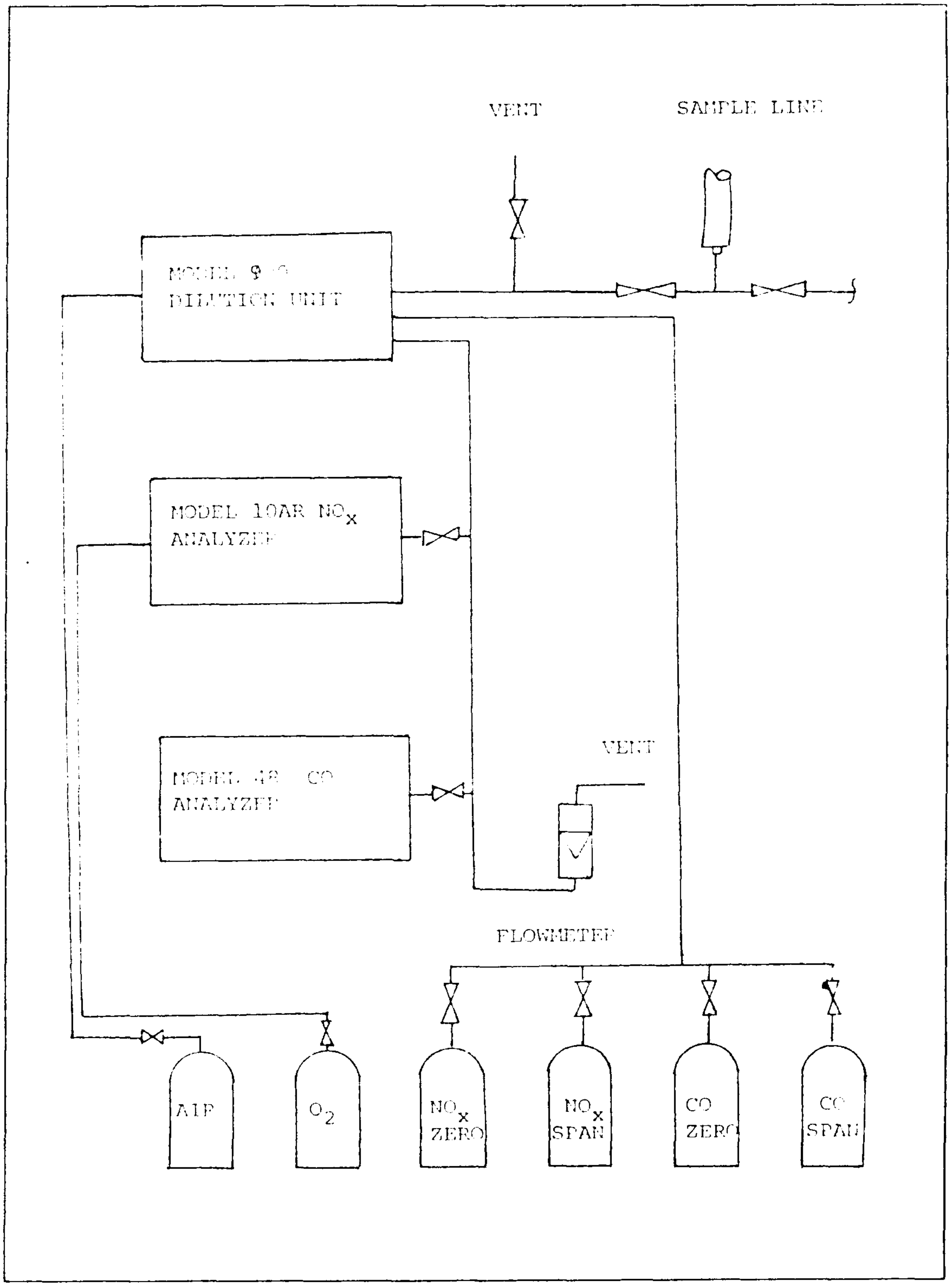


Figure 8 Schematic of Sample Gas Flow

readings of nitric oxide (NO) or a mix of oxides of nitrogen ($NO + NO_x$ or NO_x). The analyzer read in ranges from 2.5 to 10,000 parts-per-million (ppm) and had a sensitivity of .1 ppm. All readings were corrected for the dilution ratio to get the true raw sample concentration.

The operating principle for this analyzer is the chemiluminescent reaction of NO and ozone (O_3), namely

$$NO + O_3 \Rightarrow NO_2 + O_2$$

The analyzer first converted all the sample gas NO_x to NO through a thermal NO_2-to-NO converter. Then the analyzer mixed the NO with ozone from an internal generator. The resulting chemiluminescence was measured on a photomultiplier (PM) and was read on the dial. The output of the PM was linearly proportional to the NO concentration [Ref. 15].

3. Model 48 CO Analyzer

A portion of the output from the Model 900 went to the Model 48 CO Analyzer. This analysis was made using non-dispersive infrared absorption techniques. While the output was non-linear, it was linearized using stored calibration curves from computer memory [Ref. 16]. The analyzer was accurate to 0.1 ppm and read from 0.1 to 1000 ppm. Like the Model 10AR, readings were multiplied by 20, the dilution ratio, to get the raw sample concentration.

I. CONTROL ROOM

The control room was located adjacent to the test cell with the T-63 combustor and had two windows for viewing the tests. All controls for operating the fuel, air, additive pumps, and gas sampling equipment were located there. The only changes made since Behrens investigation [Ref. 12] was moving all calibration and zero gases outside the control room and plumbing them to the analyzers.

J. DATA COLLECTION

Data acquisition and reduction was accomplished by the Hewlett-Packard HP-3054A automatic data acquisition/control system located in the control room. The test data was controlled by a program (Appendix A) written in HP Basic 5.1. The program was stored on the hard disk and included subroutines for calibration of transducers, set up of gas flows, and reduction of hot run data. Transmittance data and gas concentrations were taken directly from the strip chart recorder and analyzers respectively.

III. EXPERIMENTAL PROCEDURE

Calibration of all equipment was standard operating procedure before all data runs. A checklist (Appendix B) was used to ensure no critical items were forgotten. Appendix C was developed to ensure the gas analyzers were reading accurately.

A. NO_x REDUCTION STUDIES

For NO_x studies, the gas analyzers were calibrated with zero and span gases in accordance with References 14-16. The Model 10AR required a zero gas of less than 0.1 ppm NO_x and a span gas with 220 ppm NO in nitrogen. The Model 48 was calibrated with a zero gas containing less than 0.1 ppm CO and a span gas with 104 ppm CO in air. Since both analyzers received sample air which had been filtered and diluted at a 20:1 ratio, the meter reading required a factor of 20 to get the raw sample concentration in ppm.

The program "T63NOX" (Appendix A) was written in HP BASIC and used to collect data. It contained a calibration routine which was used prior to data runs to calibrate the pressure transducers. With known pressures on the transducers, new calibration constants were calculated and entered into the program for data reduction.

The augmentor tube velocities were calculated using a Kiel probe measurement of total pressure and a wall port measurement, at the same station. A slant tube manometer read the difference. A built-in level was used to assure accurate readings to within 0.01 inches of H_2O. Probe position was measured with a linear variable differential transformer (LVDT) and output to a strip chart recorder in the control room. Catalyst bed pressure loss was measured with a U-tube manometer filled with dyed water. To allow safe remote readings, a video camera relayed both manometer readings to a monitor in the control room.

After completing the run checklist (Appendix B), gas analyzer checklist (Appendix C), and all equipment was set for a run, the combustor was ignited. The combustor was operated in accordance with Table I at fuel to air ratios of f = 0.017-0.019. Once a steady operating condition was reached, the data acquisition program was activated and the conditions were not changed for the duration of the run. The Kiel probe was traversed across the augmenter tube and the pressure readings recorded.

Run times were usually five to six minutes. The gas sampling was started upstream of the bed and lasted long enough for the NO_x and CO concentrations to stabilize. This typically took two or three minutes. The downstream sample was then taken for the balance of the run. When the concentrations stabilized, the readings were taken.

It was desired to conduct several runs using vermiculite coated with different chemicals which had been successful for Nelson [Reference 8]. The coating process for the vermiculite involved wetting the vermiculite with water and then mixing in thiourea. The thiourea was mixed 20% by weight. After thorough mixing, the vermiculite was spread in pans and baked overnight at 120° C.

Vermiculite is available in several grades. A-6 (extra coarse) is the largest with an average size of 3/8 in. Coarse averages 1/4 in (Figure 9). A method to reduce pressure loss of the bed discovered by Behrens, was to use larger size catalyst. While it had been reported [Reference 8] that A-6 grade was not as effective at NO_x reduction as the coarse grade, it was felt that the larger size would offer the least pressure loss. A-6 grade was the largest grade available and is more difficult to acquire. Extra coarse perlite (sodium-potassium-aluminum-silicate), as evaluated by Behrens, was unavailable.

B. ADDITIVE STUDIES

During the additive studies, prior to each run the Eldex additive pumping rates were set against a back pressure of 100 psi to simulate the fuel pressure in the line in the mixing chamber. The pumping rates for the pumps were measured using a graduated cylinder over a known time. As a final check of additive pump rate, the level of the reservoirs were measured before and after each run and the rate was calculated from the time of pump operation. The additive pumps were controlled from the control room.

Figure 9 Photograph of Grades A-6 and Coarse Vermiculite and Perlite

The laser was used to measure changes in transmittance during the additive studies. It was securely mounted and aimed through the forward window in the aft combustor can at the photodiode target (Figure 10). The alignment of the photodiode was adjusted for maximum power out and read on a strip chart in the control room. Prior to setting air flow rates or engine operation the window purge was turned on to prevent and loose soot from lodging on the windows.

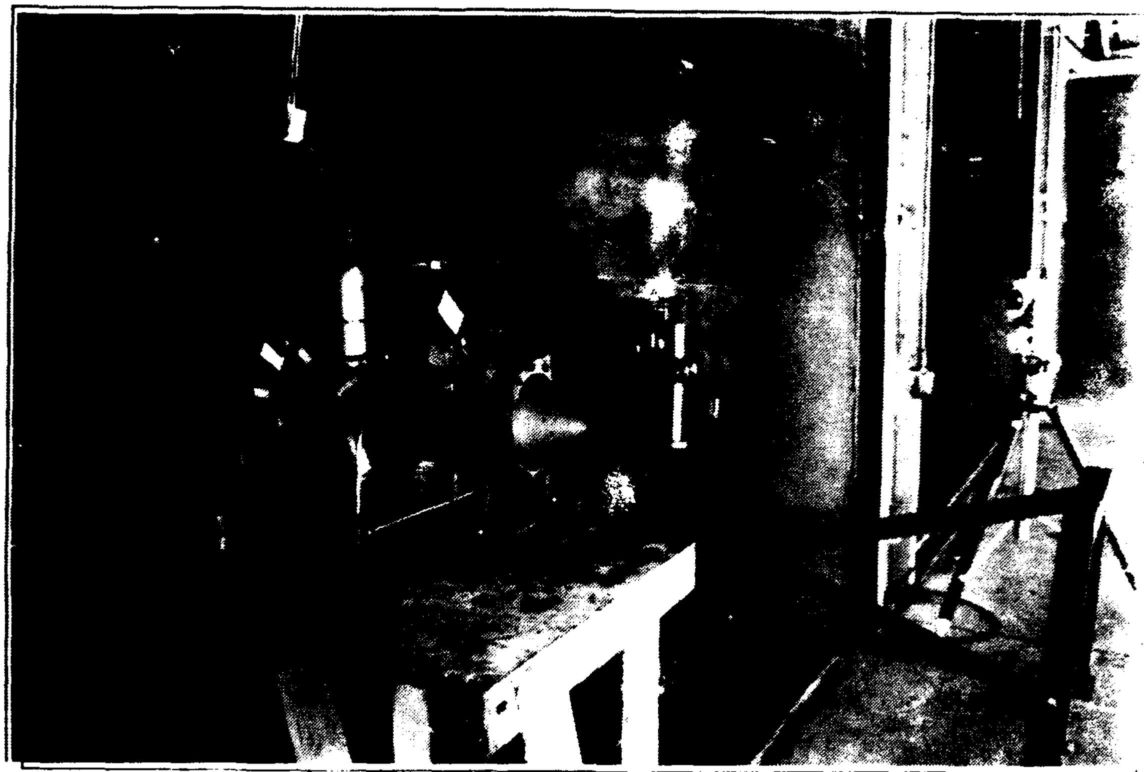


Figure 10 Photograph of Laser and IR Measurement Equipment

To measure the effects of the additives on the thermal signature of the T-63, the IR scanner was positioned in the test cell and aimed at the exhaust plume. For these runs the augmentor tube was rolled back out of the way to allow the plume to fully develop.

The CATS-E software with the IR system was programmed to average ten images three times during each run condition. At the same time the HP DACU was run with an abridged version of "T63NOX" to record P_b, T_{ex}, and T_{ext}. Appendix E was used for guidance during the short run period.

IV. RESULTS AND DISCUSSION

A. NO_x REDUCTION STUDIES

Shown in Table II is a synopsis of the NO_x reduction runs using vermiculite. Appendix D contains the computer output for each data run. NAPC 4 was used for all runs.

TABLE IV NO_x REDUCTION SUMMARY

Parameter	Run 1	Run 2	Run 3
catalyst used	Vermiculite A-6 coated with 20% wt thiourea	Vermiculite coated with 20% wt thiourea	Plain vermiculite 50-50 mix A-6 and coarse
bed depth (in.)	6	6	16
bed screen spacing (in.)	16	18	41
space velocity	185,760 hr^{-1}	95,000 hr^{-1}	43,000 hr^{-1}
m_a (lbm/sec)	2.29	2.21	2.19
f	0.019	0.018	0.019
V_{avg} (ft/sec)	25.7	13.2	15.8
press. loss (in. H_2O)	34	36	32
AR	0.5	no AR, mass lost	no AR, mass lost
T_{aug} (deg. R)	904	991	998
T_{exit} (deg. R)	1685	1700	1731

Parameter	Run 1	Run 2	Run 3
CO (ppm) up/down	832/470	1340/920	1117/856
NO_x (ppm) up/down	17/14	52/42	38/34
NO_x % reduction	17.6%	19%	11%

Notes: Run 1-Screen failed during run. NO_x reduction not sustained.

Runs 2 & 3-Augmentation less than 0. Mass flow lost out the front of the tube.

There were three major problems with the use of vermiculite in the test cell for NO_x reduction:

- It did not reduce the NO_x enough in the present installation to make it practicable.
- The flow resistance as presently configured was 36 in. H_2O and far in excess of that permitted in a test cell.
- The cost of the chemical for adding ammonia (thiourea) is probably too expensive for economic use.

In the USAF funded study [Ref. 8] the space velocities (defined as bed volumes/unit time) ranged from 5,000 to 60,000 hr^{-1}. This gave the NO_x molecules a much longer time to react on the vermiculite. It would be possible to reduce the space velocity, but it would require extensive modifications to existing test cells.

The pressure loss through the bed is possibly the most important problem. Engines in the test cell are very sensitive to back pressure, and a resistance of as little as two in. H_2O can invalidate the test results. When the space velocity is reduced, the pressure loss will be reduced a certain extent, however, not entirely. The rough shaped vermiculite tends to become packed and block the flow for any bed thickness.

In order to achieve the high reductions obtained in other studies it is necessary to coat the vermiculite with a chemical containing ammonia. The cost of the thiourea (which has given up to 98% NO_x reduction) is quite high when purchased in the quantities needed for a test cell. A 2 Kg box cost $50.

B. ADDITIVE STUDIES

The additive testing occurred after the NO_x testing. During the additive studies the T-63 was reconfigured for maximum soot production by installing the quench, reducing main air pressure to 600 psi and connecting the window purge gas. Two data runs were made with the augmentor tube removed, additive pumps installed and calibrated, IR camera positioned, and laser installed. In both runs all parameters were kept the same with the exception of the additive. The following effects of the additives were measured: plume opacity (soot concentration assuming D_{32} constant), burner efficiency, and temperature distribution within the exhaust plume. NAPC 3 fuel was used for all runs.

1. Plume Opacity

Data were taken in accordance with Appendix E. Transmittance output is shown in Appendix D. For both additives, 100% transmittance was taken after the fuel was shut off, but while the purge and main air flows were on.

The Wynn's additive 15/590 had no effect on the transmittance through the combustor of the T-63 when used at the recommended rate of 22.5 ml/gal, or 0.6% by volume.

The Catane TM (ferrocene) has been studied previously in the present lab and has proven effective in reducing the mass concentration of the soot. In the present installation, using NAPC 3 fuel, the Catane TM reduced the sooting by 6.2% when used at the rate of 26.5 ml/gal.

2. Burner Efficiency

It was realized that burner efficiency is very high in most gas turbine combustors operating at high pressure. However, liquid fueled ramjets do not operate at such high pressures or combustion efficiencies. The T-63 operates at typical ramjet pressure. There was some question that with a reduction in soot there might be some increase in the heat released. Further, the Wynn's Co. had provided a body of data which showed that 2-3% increase in fuel efficiency was obtained when the 15/590 was used in diesel powered trucks. The equation for sonically choked flow,

$$\dot{m} = C_D \frac{P_c A_{th}}{\sqrt{R T_t}} \sqrt{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

becomes for a given engine in which γ and R are essentially constant,

$$\dot{m} = \frac{k P_c}{\sqrt{T_t}}$$

In the present tests, P_c and T_t were measured at the entrance to the exhaust nozzle (P_c and T_{ex1}).

The data for a test conditions were averaged and k was calculated. This was done for all conditions and the k values compared. Table V summarizes the result.

TABLE V EFFICIENCY RESULTS

Condition	m (lbm/sec)	T_{ex1} °R	P_c (psi) measured	k calculated
w/o Catane	1.94	1625	98.9	1.265
w Catane	1.925	1586	97.0	1.265
w/o 15/590	1.922	1582	97.9	1.281
w 15/590	1.905	1595	97.5	1.281

From Table V it can be seen from the essentially unchanged values of k with either additive, that there was no increase in efficiency as defined by measured P_t and T_t.

3. Infrared Signature Studies

The exhaust plume thermal distributions obtained for the four conditions shown in Table VI are presented in Figures 11-14. It was observed that the temperature at the nozzle exhaust (M=1) had maximum values of approximately 233°C. This would imply nozzle inlet stagnation temperatures of approximately 275°C.

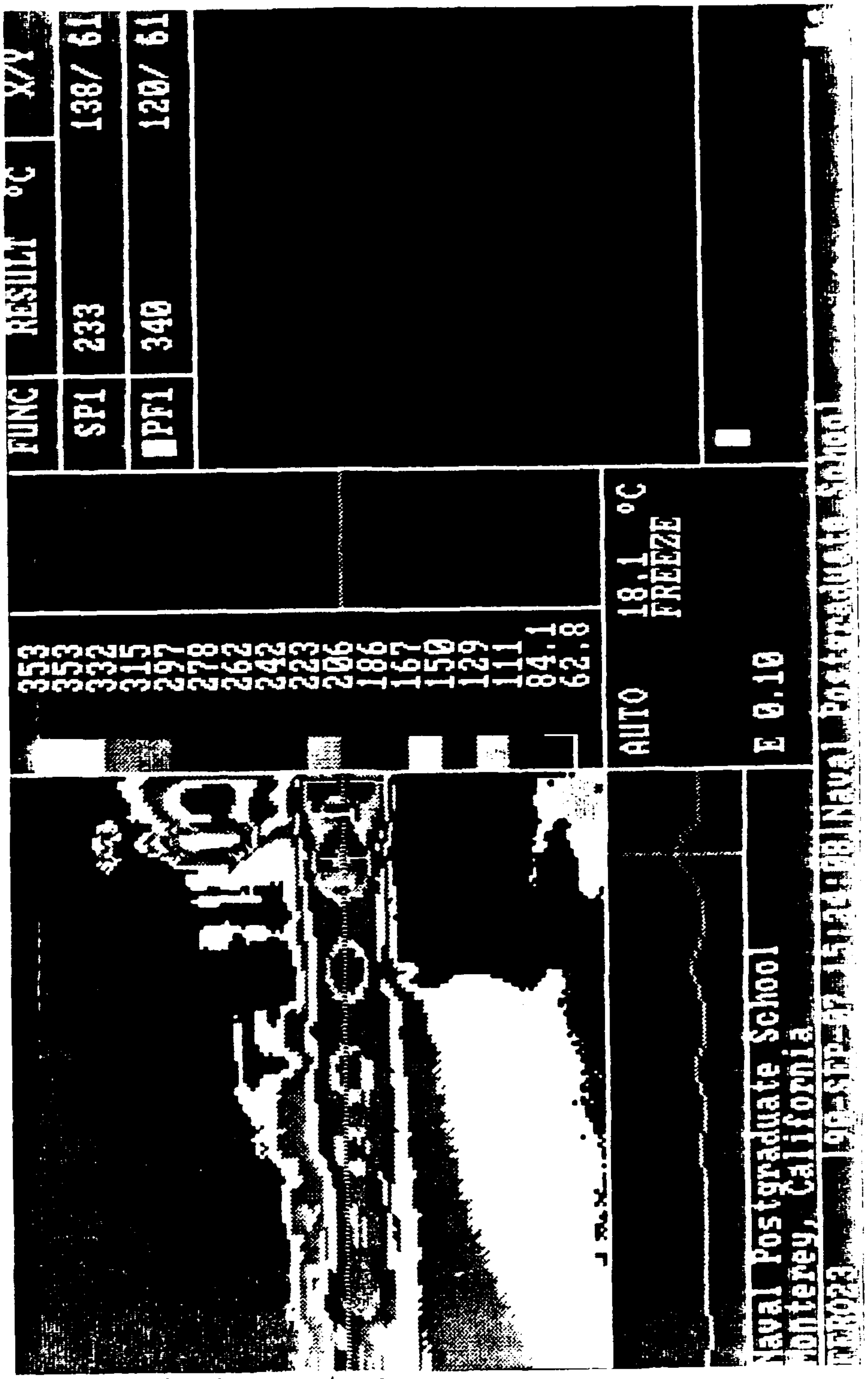


Figure 11 Plume w/o Catane

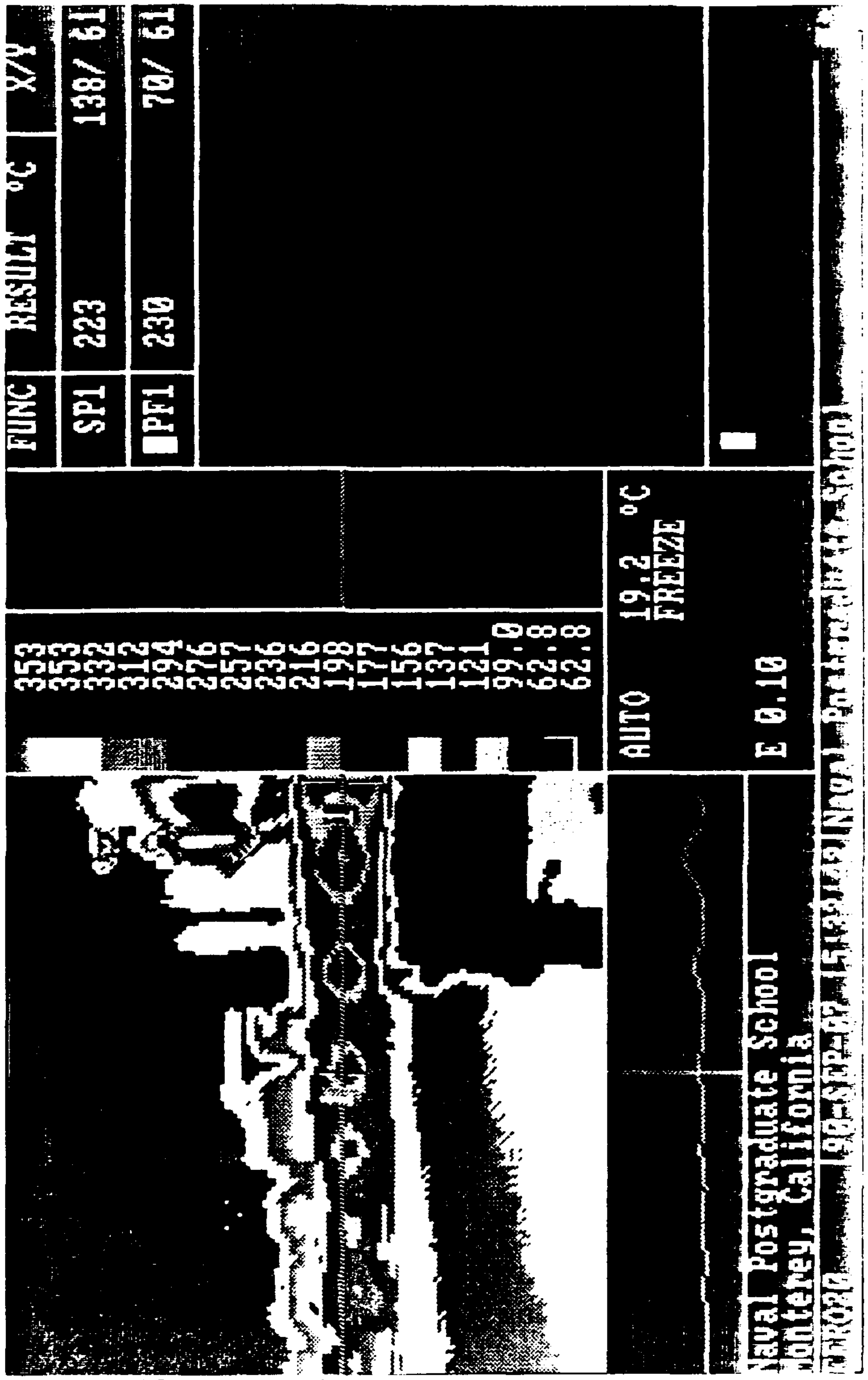


Figure 12 Plume with Catane TM

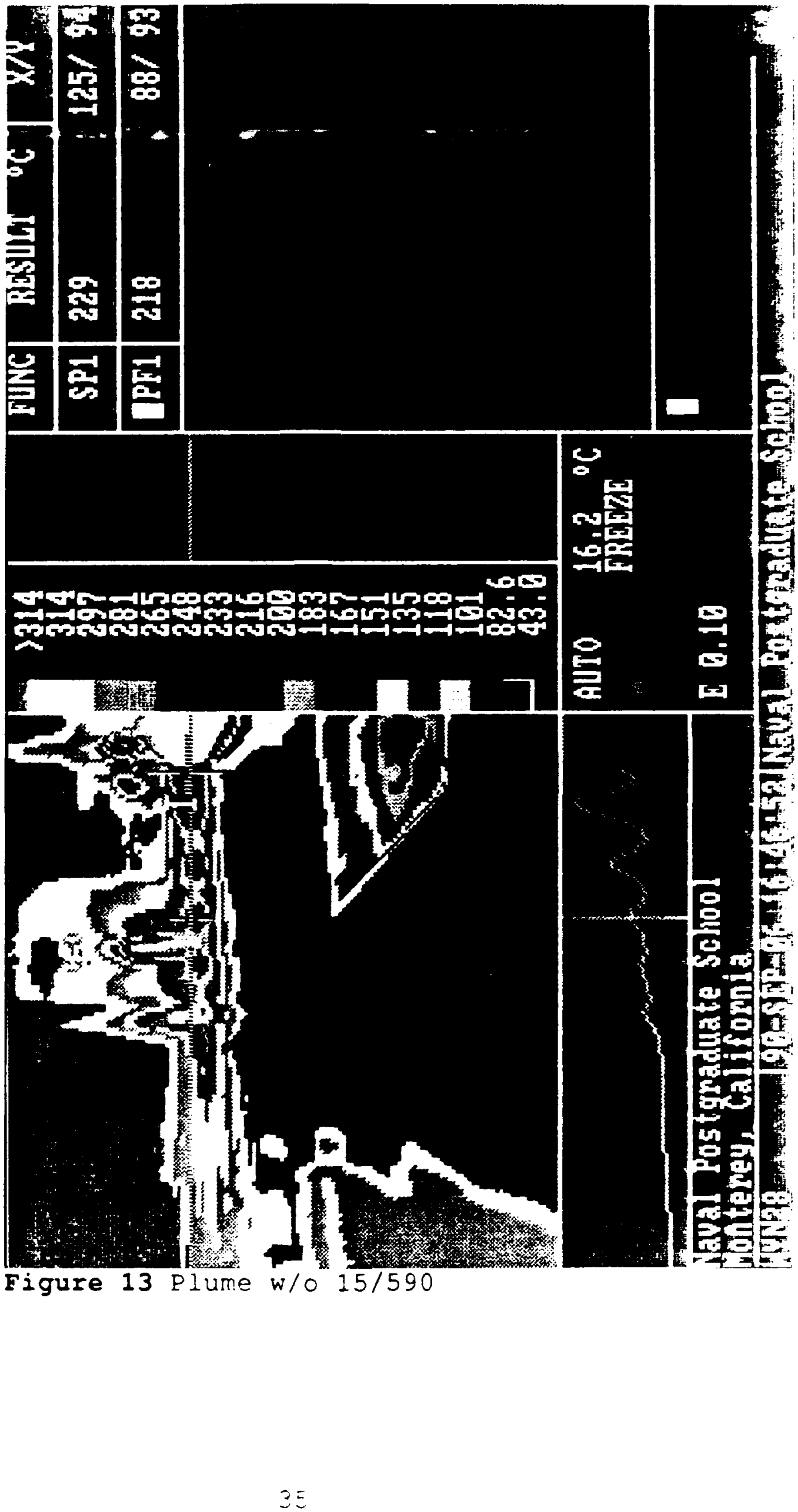


Figure 13 Plume w/o 15/590

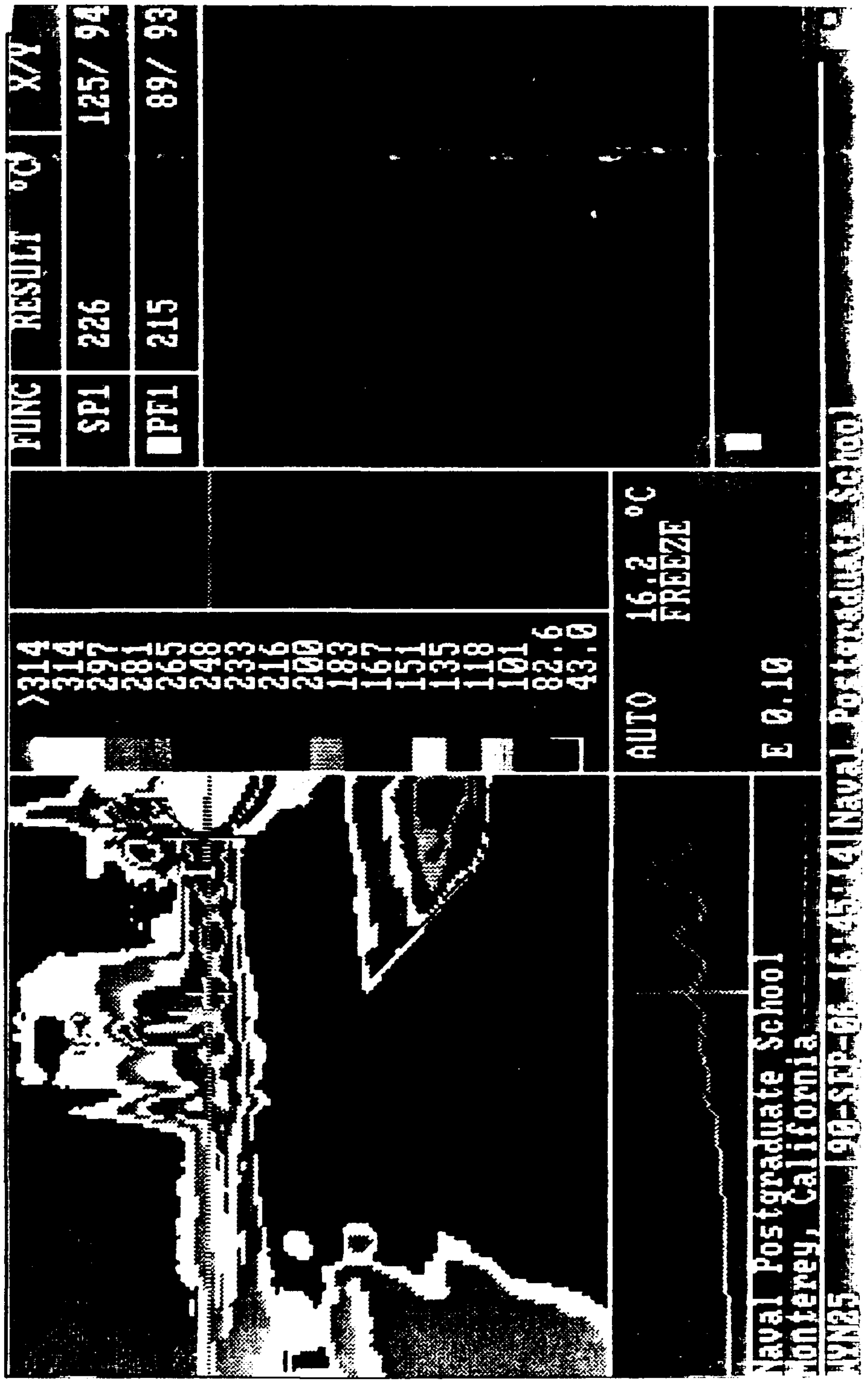


Figure 14 Plume with 15/590

The temperature measured at the nozzle entrance, T_{ex2}, was higher than the value expected. It was surmised that the thermocouple was located in a hot recirculation zone and yielded abnormally high temperatures. Using an energy balance for the combustor and quench air flows an average "T_{mix}" could be calculated. This yielded a lower "effective" T_{ex2}, but still not as low as expected from the plume temperature measurement. It was noted following every run that the combustor was quite hot, in fact it frequently glowed dull red during a run. These heat losses are believed to account for much of the lower than expected plume temperatures. In addition, the exact emissivity of the gas could not be set in the Agema system. This variance from the correct value is discussed below and caused the temperatures read from the IR system to be somewhat low.

Although every effort was made to maintain steady flow rates during the run, there were small changes in the air and fuel flows during the approximately five minute run. These were probably due to temperature changes and pressure regulator drifts. These changes in fuel-air ratio (f) can be seen in Appendix D. In order to properly compare the plume temperatures obtained with and without the additive, a correction was required to put them on the same f basis. An equilibrium adiabatic combustion code was used [Ref. 17]. Micro NewPEP was run several times using JP4 with values of f around the values actually observed. This gave the approximate theoretical temperature at the throat of the choked exhaust nozzle. Approximate values of $\Delta T^{*}/\Delta f$ were then generated to provide corrections of the measured temperature data to the same value of f.

The IR pictures generated were analyzed with the spotmeter function at the same pixel location of the image, both with and without the additive. The location chosen was the throat of the converging exhaust nozzle. The differences were calculated and are summarized in Table V.

TABLE VI SUMMARY OF IR MEASUREMENTS

Condition Fig. No.	f	T_{mix} °C	T_{ex2} °C	T^{*} °C, IR camera
w/o Catane Fig. 13	0.0171	475	521	233
Catane TM Fig. 14	0.0163	458	504	223
ΔT^{*} °C (T^{*}w/o-T^{*}w) measured				+10
ΔT^{*} °C for same f, expected				+26

Condition Fig. No.	f	T_{mix} °C	T_{ex2} °C	T^* °C, IR camera
w/o 15/590 Fig. 15	0.0169	456	505	229
15/590 Fig. 16	0.017	460	511	226
Δ T^* °C (T^*w/o-T^*w) measured				+3
Δ T^* °C for same f, expected				+3

The emissivity of the exhaust plume must be known for exact temperatures to be displayed on the image. The emissivities of CO_2 and H_2O are each approximately 0.06 for a 4 in. diameter nozzle at 1000°F [Ref. 17]. However, the Agema system can not be set below 0.1. Using 0.06 would further increase the measured temperature of the plume to values closer to the values expected from the nozzle flow. There are, of course, many other species in the exhaust plume. However, they are weak emitters.

In the run with the Catane additive, it was expected that the temperature would decrease from 233° C to 207° C for the conditions without the additive, based on the changes in f alone. However, it was measured that the temperature decreased to only 223° C. Therefore, when the data were corrected to th same f value, the plume IR signature actually increased slightly.

The temperatures for the Wynn's 15/590 tests were expected to remain almost constant for the condition with the additive, based on changes in f alone. Yet, the measurements showed that the temperature decreased slightly (3° C). These slight changes were within the realm of data uncertainty and there was considered to be no significant change in the plume thermal distribution.

V. CONCLUSIONS AND RECOMMENDATIONS

A. NO_x REDUCTION

With the pressure loss experienced in the present work, and by Behrens, it can be concluded that vermiculite in the form utilized will not be effective in reducing the NO_x emissions from US Navy or US Air Force test cells. In addition, much larger surface areas will be required with extensive modification to the existing structures. If the vermiculite could be formed into a honeycomb shape it might be possible to reduce the pressure loss. There is still the problem of reducing the space velocity in order to increase the NO_x reduction effectiveness. Even a SCR system will require enlargement of the augmentor tube to accommodate the increased volume of the catalyst bed. Future effort might be directed at developing a larger catalyst bed with custom-formed large size vermiculite. The effectiveness and amount of slip from a SCR system should be investigated under military test cell applications.

B. ADDITIVE STUDIES

In the T-63 combustor, the Wynn's 15/590 was ineffective in reducing the soot. It also had no effect on the efficiency of the combustor. This was not entirely unexpected since the efficiency of this combustor was already quite high.

When all factors such as heat losses and emissivity corrections are taken into account, the Agema IR Imaging System can give accurate nonintrusive measurements of jet exhaust stream thermal distributions.

Neither of the additives tested were effective in reducing the IR signature of a ramjet type exhaust plume. It is recommended that further study be carried out to investigate the effects of different fuels and different additive mixture ratios on the plume IR signature.

APPENDIX A

"T63NOX" Computer program

```
10   ! T63 VERSION 5, JAN 1990
20   PRINTER IS 1
30   ! T63 COMBUSTOR DATA ACQUISITION AND REDUCTION PROGRAM
40   ! THIS PROGRAM IS DIVIDED INTO FIVE PARTS:
50   !     (1) VARIABLE DEFINITIONS AND NOMENCLATURE
60   !     (2) TRANSDUCER CALIBRATIONS
70   !     (3) FLOW CHECKS AND NOZZLE CALCULATIONS
80   !     (4) THE TEST SEQUENCE AND DATA COLLECTION
90   !     (5) POST-RUN OPERATIONS, DATA REDUCTION AND SHUTDOWN
100  !*******************************************************************************
110  !(1) VARIABLE DEFINITIONS AND NOMENCLATURE
120  !*******************************************************************************
130  !  SYMBOL              DEFINITION
140  !  A                 ANALOG CHANNEL NUMBER
150  !  Aair              THROAT AREA,AIR FLOW SONIC CHOKE, SQ. IN.
160  !  Ahf               THROAT AREA,HEATER FUEL SONIC CHOKE, SQ.IN
170  !  Aho               THROAT AREA,HEATER OXYGEN SONIC CHOKE, SQ.IN.
180  !  Bpair             BYPASS AIR FLOWRATE
190  !  Cdair             DISCHARGE COEFFICIENT, AIR SONIC CHOKE
200  !  Cdhf              DISCHARGE COEFFICIENT, HEATER  FUEL SONIC CHOKE
210  !  Cdho              DISCHARGE COEFFICIENT, HEATER O2 SONIC CHOKE
220  !  Dairchoke         AIR SONIC CHOKE DIAMETER
230  !  Dbpchoke          BYPASS AIR SONIC CHOKE DIAMETER
240  !  Date$             Test Date  Mo-Day-Yr
250  !  Dhfchoke          AIR HEATER FUEL SONIC CHOKE DIAMETER
260  !  Dhochoke          AIR HEATER OXYGEN SONIC CHOKE DIAMETER
270  !  Fuelid$           FUEL IDENTIFICATION
280  !  Gc                32.174
290  Gc=32.174
300  !  Heaterfuel        HEATER FUEL IDENTIFICATION
310  !
320  !  Kmair             AIR SONIC CHOKE FLOW RATE CONSTANT
330  !  Kmfuel            FUEL FLOW METER RATE CONSTANT (GPM/VOLT
340  !  Kmhf              HEATER FUEL SONIC CHOKE FLOW RATE CONSTANT
350  !  Kmho              HEATER O2 SONIC CHOKE FLOW RATE CONSTANT
360  !  Kp                PRESSURE TRANSDUCERS CONSTANT (PSI/VOLT)
370  !  Mair              AIR FLOW RATE, LBM/SEC
380  !  Maird             DESIRED AIR FLOW RATE, LBM/SEC
390  !  Mfuel             FUEL FLOW RATE, GPM
400  !  Mfueld            DESIRED FUEL FLOW RATE, GPM
410  !  Mhf               HEATER FUEL FLOW RATE, LBM/SEC
420  !  Mhfd              DESIRED HEATER FUEL FLOW RATE LBM/SEC
430  !  Mho               HEATER OXYGEN FLOW RATE, LBM/SEC
440  !  Mhod              DESIRED HEATER OXYGEN FLOW RATE, LBM/SEC
450  !  Pa                PRESSURE, AIR SONIC CHOKE, PSIA
460  !  Pbpa              PRESSIRE, BYPASS AIR SONIC CHOKE, PSIA
470  !  Pbar              BAROMETRIC PRESSURE, PSIA
480  !  Pc                PRESSURE, COMBUSTION CHAMBER, PSIA
490  !  Phf               PRESSURE, HEATER FUEL SONIC CHOKE, PSIA
500  !  Pho               PRESSURE, HEATER OXYGEN SONIC CHOKE, PSIA
510  !  Ta                TEMPERATURE, AIR SONIC CHOKE, R
520  !  Tbpa              TEMPERATURE, BYPASS AIR SONIC CHOKE, R
530  !  Taugup            TEMPERATURE, AUGMENTOR TUBE UPSTREAM CATALYST, R
540  !  Taugdn            TEMPERATURE, AUGMENTOR TUBE DOWNSTREAM CATALYST, R
550  !  Testno$           TEST I.D NO.
560  !  Thf               TEMPERATURE, HEATER FUEL SONIC CHOKE, R
570  !  Tho               TEMPERATURE, HEATER O2 SONIC CHOKE, R
580  !  Tcir              TEMPERATURE, COMBUSTOR AIR INLET (HEATER OUTLET), R
590  !  Tcird             TEMPERATURE, DESIRED COMBUSTOR AIR INLET, R
600  !  Tex1              TEMPERATURE, COMBUSTOR EXHAUST UPSTREAM OF QUENCH, R
610  !  Tex2              TEMPERATURE, COMBUSTOR EXHAUST DOWNSTREAM OF QUENCH, R
620  BEEP 1000,.1
630  PRINT USING "@"
640  PRINT USING "A,/"
```

```
650  PRINT " T63 DATA ACQUISITION "
660  PRINT USING "5/"
670  PRINT "TURN THE PRINTER ON LINE"
680  CLEAR 709
690  CLEAR 722
700  ! THE RECORDED VARIABLES (VOLTAGES) AND LOCATIONS ARE:
710  ! (NOTE: THE MAXIMUM ALLOWABLE VOLTAGE INTO THE SYSTEM IS 1.2 VOLTS)
720  !
730  ! VARIABLE                               3497 DACU SCANNER NUMBER 0__
740  !
750  ! Pa-------                              24----------------------
760  ! Pbpa                                   24
770  ! Pc                                     23
780  ! Mfuel                                  25
790  ! Pnf                                    22
800  ! Pno                                    21
810  ! Ta                                     60
820  ! Tcin (inlet air)                       61
830  ! Tex1 (upstream of quench)              62
840  ! Tex2 (downstream of quench)            63
850  ! Tho                                    64
860  ! Thf                                    65
870  ! Tavg p                                 66
880  ! Tavgd1                                 67
890  ! Tavgd2                                 68
900  !ALL FLOW RATES ARE CALCULATED USING THE ONE-DIMENSIONAL, ISENTROPIC
910  !FLOW EXPRESSIONS WITH FIXED PROPERTIES. SMALL SONIC NOZZLES HAVE
920  !MEASURED DISCHARGE COEFFICIENTS. THE AIR FLOW NOZZLE USES AN ASSUMED
930  !DISCHARGE COEFFICIENT (Cd) OF 0.97.
940  !
950  !M (LBM/SEC)=Cd*P*A*Km/T^.5
960  !
970  !Km IS THE GAS-DEPENDENT SONIC CHOKE FLOW RATE CONSTANT
980  !
990  !Km=SQR((Gamma*Gc/R)*(2/(Gamma+1))^((Gamma+1)/(Gamma-1)))
1000 !
1010 ! APPROPRIATE CONSTANTS ARE:
1020 !
1030 ! GAS     MOLECULAR WT.   GAS CONST.     CP      GAMMA      Km
1040 !
1050 ! AIR        28.97          53.3        .240     1.40      .5320
1060 ! O2         32.0           48.3        .217     1.40      .5589
1070 ! CH4        16.03          96.4        .593     1.32      .3976
1080 ! N2         28.01          55.16       .248     1.40      .5229
1090 ! H2          2.016        766.5       3.419     1.405     .1405
1100 !
1110 Gammaair=1.40
1120 Gammaox=1.40
1130 Gammahf=1.405
1140 Kmair=.5320
1150 Kmho=.5589
1160 Kmhf=.1405
1170 Rair=53.3
1180 Rho=48.3
1190 Rhf=766.5
1200 Dairchoke=.42
1210 Dbpchoke=.237
1220 Dhochoke=.0700
1230 Dhfchoke=.040
1240 Mairc=1.9
1250 Mbpaird=.59
1260 Mfueld=.33
1270 Mhfd=.00295
1280 Mhod=.0205
1290 PRINT USING "6/"
1300 INPUT "Input the barometric pressure in mm of Hg",Pmm
1310 Pbar=Pmm*.019337
1320 Cdair=.97
1330 Cdhf=.97
1340 Cdho=.97
```

```
1350 !ALL THERMOCOUPLES ARE CHROMEL vs. ALUMEL (TYPE K) WITH
1360 !ELECTRONIC ICE POINTS. TEMPERATURE READINGS (VOLTAGES) ARE
1370 !CONVERTED TO DEGREES RANKINE (R) PER "INDUSTRIAL INSTRUMENTATION" BY
1380 !D.P. ECKMAN (PAGE 369). THIS CALCULATION IS PERFORMED IN SUBROUTINE
1390 !Tcalc. TEN VOLTAGE INTERVALS ARE USED BETWEEN 460 AND 2460 R.
1400 PRINT USING "@"
1410 PRINT USING "6/"
1420 INPUT "WILL THE AUGMENTOR TUBE BE USED? (Y/N)",Aug$
1430 IF Aug$="Y" THEN Aug=1
1440 IF Aug$="N" THEN Aug=0
1450 PRINT USING "@"
1460 PRINT USING "6/"
1470 INPUT "WILL THE AIR HEATER BE USED?  (Y/N)",Zz$
1480 IF Zz$="Y" THEN Ht=1.
1490 IF Zz$="N" THEN Ht=0.
1500 PRINT USING "@"
1510 PRINT USING "6/"
1520 INPUT "WILL YOU USE PRE-INITIALIZED VALUES OF CALIBRATION CONSTANTS AND ZE
ROS? (Y/N)",Zz$
1530 IF Zz$="Y" THEN GOTO Initial
1540 GOTO Transcal
1550 Tcalc: !
1560 !***************************************************************
1570 !    ***VOLTAGE TO TEMPERATURE (RANKINE) CONVERSION SUBROUTINE***
1580 !***************************************************************
1590          IF Volts<.00153 THEN T=((Volts+.00068)/.0000220)+460
1600          IF Volts>=.00153 AND Volts<.00382 THEN T=((Volts-.00153)/.000023
0)+560
1610          IF Volts>=.00382 AND Volts<.00609 THEN T=((Volts-.00382)/.000022
7)+660
1620          IF Volts>=.00609 AND Volts<.00831 THEN T=((Volts-.00609)/.000022
2)+760
1630          IF Volts>=.00831 AND Volts<.01056 THEN T=((Volts-.00831)/.000022
5)+860
1640          IF Volts>=.01056 AND Volts<.01285 THEN T=((Volts-.01056)/.000022
9)+960
1650          IF Volts>=.01285 AND Volts<.01518 THEN T=((Volts-.01285)/.000023
3)+1060
1660          IF Volts>=.01518 AND Volts<.01752 THEN T=((Volts-.01518)/.000023
4)+1160
1670          IF Volts>=.01752 AND Volts<.01988 THEN T=((Volts-.01518)/.000023
6)+1260
1680          IF Volts>=.01988 AND Volts<.02225 THEN T=((Volts-.01988)/.000023
7)+1360
1690          IF Volts>=.02225 AND Volts<.02463 THEN T=((Volts-.02225)/.000023
8)+1460
1700          IF Volts>=.02463 AND Volts<.02698 THEN T=((Volts-.02463)/.000023
5)+1560
1710          IF Volts>=.02698 AND Volts<.02932 THEN T=((Volts-.02698)/.000023
7)+1660
1720          IF Volts>=.02932 AND Volts<.03165 THEN T=((Volts-.02932)/.000023
3)+1760
1730          IF Volts>=.03165 AND Volts<.03393 THEN T=((Volts-.03165)/.000022
8)+1860
1740          IF Volts>=.03393 AND Volts<.03619 THEN T=((Volts-.03393)/.000022
6)+1960
1750          IF Volts>=.03619 AND Volts<.03843 THEN T=((Volts-.03619)/.000022
4)+2060
1760          IF Volts>=.03843 AND Volts<.04062 THEN T=((Volts-.03843)/.000021
9)+2160
1770          IF Volts>=.04062 AND Volts<.04278 THEN T=((Volts-.04062)/.000021
6)+2260
1780          IF Volts>=.04278 AND Volts<.04491 THEN T=((Volts-.04278)/.000021
6)+2360
1790          IF Volts>=.04491 THEN T=((Volts-.04278)/.0000216)+2460
1800     RETURN
1810 Initial:
1820 ! Initialized values of zeros and calibration constants for all transducers
```

```
1830 Testno$="KUET1"
1840 Date$="8-01-78"
1850 Fuelid$="NAFC4"
1860 Heaterfuel$="HYDROGEN"
1870 Vpa0=.0017222
1880 Kpa=33368.37
1890 Vpc0=-.176573
1900 Kpc=845.73678
1910 Vpho0=.0356919
1920 Kpho=671.61413
1930 Vphf0=-.116253
1940 Kphf=1356.9902
1950 Kmfuel= 5
1960 Transcal: !
1970  !*******************************************************************
1980  !(2) TRANSDUCER CALIBRATIONS
1990  !*******************************************************************
2000  !THERE ARE 4 PRESSURE TRANSDUCERS THAT MUST BE CALIBRATED
2010  !TRANSDUCER LINEARITY MUST BE VERIFIED BEFORE THIS
2020  !CALIBRATION PROCEDURE IS EMPLOYED. THE ORDER OF CALIBRATION IS AS
2030  !FOLLOWS: Pa, Pc, Phf, Pho
2040  !THE FOLLOWING TWO LINES SET UP 722 AND 709 FOR DATA ACQUISITION!
2050 !CLEAR 709
2060  CLEAR 722
2070  REMOTE 709
2080  OUTPUT 722;"L1R11STNZ110STIT40X1"
2090  INPUT "DO YOU WANT TO CALIBRATE TRANSDUCERS? (Y/N)",Yy$
2100  IF Yy$="N" THEN GOTO Endcal
2110  INPUT "DO YOU WANT CONSECUTIVE ORDER OF CALIBRATION?(Y/N)",Yy$
2120  IF Yy$="Y" THEN GOTO Consec
2130  INPUT "DO YOU WANT TO RECALIBRATE Pa? (Y/N)",Yy$
2140  IF Yy$="Y" THEN GOTO Pacal
2150  PRINT USING "@"
2160 Pc: !
2170  INPUT "DO YOU WANT TO RECALIBRATE Pc? (Y/N)",Yy$
2180  IF Yy$="Y" THEN GOTO Pccal
2190  PRINT USING "@"
2200  IF Ht=0 THEN GOTO Endcal
2210 Phf:                    !
2220  INPUT "DO YOU WANT TO RECALIBRATE Phf? (Y/N)",Yy$
2230  IF Yy$="Y" THEN GOTO Phfcal
2240  PRINT USING "@"
2250 Pho:                    !
2260  INPUT "DO YOU WANT TO RECALIBRATE Pho? (Y/N)",Yy$
2270  IF Yy$="Y" THEN GOTO Phocal
2280  GOTO Endcal
2290 Consec:                 !
2300  Cons=1
2310 Pacal: !
2320  !*******************************************************************
2330  PRINT USING "2/"
2340  PRINT "** CALIBRATION OF Pa, THE AIR SONIC CHOKE PRESSURE TRANSDUCER**"
2350  PRINT USING "2/"
2360  !**************************************
```

```
     !************************************************************
2370 Pa0cal:  !
2380  PRINT " ***** Z E R O   P R E S S U R E *****"
2390  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2400  DISP "HIT CONTINUE WHEN READY TO TAKE ZERO READING"
2410  PAUSE
2420  REMOTE 709
2430  OUTPUT 709;"AC24"
2440  WAIT 2
2450  OUTPUT 722;"T3"
2460  ENTER 722;Vpa0
2470  PRINT "Vpa0= ";Vpa0
2480  BEEP
2490  INPUT "READING OK? (Y/N)",Zz$
2500  IF Zz$="N" THEN GOTO Pa0cal
2510 Pamaxcal:  !
2520  PRINT USING "@"
2530  PRINT "     ***** C A L I B R A T I O N  *****"
2540  PRINT "APPLY MAXIMUM PRESSURE USING THE DEAD-WEIGHT TESTER"
2550  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pamax
2560  DISP "HIT CONTINUE WHEN READY"
2570  PAUSE
2580  REMOTE 709
2590  OUTPUT 709;"AC24"
2600  WAIT 2
2610  OUTPUT 722;"T3"
2620  ENTER 722;Vpamax
2630  PRINT "Vpamax=";Vpamax,"Pamax= ";Pamax
2640  Kpa=(Pamax)/(Vpamax-Vpa0)
2650  PRINT "Kpa= ";Kpa
2660  BEEP
2670  INPUT "READING OK? (Y/N)",Zz$
2680  IF Zz$="N" THEN GOTO Pamaxcal
2690  IF Cons=1 THEN GOTO Pccal
2700 Pccal: !
2710  !*************************************************************
2720  PRINT USING "@"
2730  PRINT "**CALIBRATION OF Pc, THE T63 CHAMBER PRESSURE TRANSDUCER**"
2740  !*************************************************************
2750 Pc0cal:  !
2760  PRINT "**** ZERO PRESSURE ****"
2770  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
2780  DISP "HIT CONTINUE WHEN READY"
2790  PAUSE
2800  REMOTE 709
2810  OUTPUT 709;"AC23"
2820  WAIT 2
2830  OUTPUT 722;"T3"
2840  ENTER 722;Vpc0
2850  PRINT "Vpc0=";Vpc0
```

```
2860  BEEP
2870  INPUT "READING OK?  (Y/N)",Zz$
2880  IF Zz$="N" THEN GOTO Pc0cal
2890 Pcmaxcal:  !
2900  PRINT USING "@"
2910  PRINT " **** CALIBRATION  ****"
2920  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
2930  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Pcmax
2940  DISP "HIT CONTINUE WHEN READY"
2950  PAUSE
2960  REMOTE 709
2970  OUTPUT 709;"AC23"
2980  WAIT 2
2990  OUTPUT 722;"T3"
3000  ENTER 722;Vpcmax
3010  PRINT "Vpcmax=";Vpcmax,"Pcmax=";Pcmax
3020  Kpc=Pcmax/(Vpcmax-Vpc0)
3030  PRINT "Kpc= ";Kpc
3040  BEEP
3050  INPUT "READING OK? (Y/N)",Zz$
3060  IF Zz$="N" THEN GOTO Pcmaxcal
3070  IF Ht=0. THEN GOTO Fincal
3080  IF Cons=1 THEN GOTO Phfcal
3090  GOTO Fhf
3100 Phfcal:!
3110  !*********************************************************************************
3120  PRINT USING "@"
3130  PRINT "**CALIBRATION OF Phf , THE T63 AIR HEATER FUEL TRANSDUCER**"
3140  !*********************************************************************************
3150 Phf0cal:  !
3160  PRINT "****ZERO PRESSURE****"
3170  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3180  DISP "HIT CONTINUE WHEN READY"
3190  PAUSE
3200  REMOTE 709
3210  OUTPUT 709;"AC22"
3220  WAIT 2
3230  OUTPUT 722;"T3"
3240  ENTER 722;Vphf0
3250  PRINT "Vphf0=";Vphf0
3260  BEEP
3270  INPUT "READING OK?  (Y/N)",Zz$
3280  IF Zz$="N" THEN GOTO Phf0cal
3290 Phfmaxcal:  !
3300  PRINT USING "@"
3310  PRINT "****CALIBRATION****"
3320  DISP "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3330  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phfmax
3340  DISP "HIT CONTINUE WHEN READY"
3350  PAUSE
3360  REMOTE 709
3370  OUTPUT 709;"AC22"
3380  WAIT 2
3390  OUTPUT 722;"T3"
3400  ENTER 722;Vphfmax
3410  PRINT "Vphfmax=";Vphfmax,"Phfmax=";Phfmax
3420  Kphf=Phfmax/(Vphfmax-Vphf0)
3430  PRINT "Kphf=";Kphf
3440  BEEP
3450  INPUT "READING OK? (Y/N)",Zz$
3460  IF Zz$="N" THEN GOTO Phfmaxcal
3470  IF Cons=1 THEN GOTO Phocal
3480  GOTO Pho
3490 Phocal:!
3500  !*********************************************************************************
3510  PRINT USING "@"
3520  PRINT "**CALIBRATION OF Pho, THE AIR HEATER OXYGEN PRESSURE TRANSDUCER**"
3530  !*********************************************************************************
```

```
3540 Phocal:  !
3550  PRINT "****ZERO CALIBRATION****"
3560  PRINT "INSURE THAT NO PRESSURE IS APPLIED TO THE TRANSDUCER"
3570  DISP "HIT CONTINUE WHEN READY"
3580  PAUSE
3590  REMOTE 709
3600  OUTPUT 709;"AC21"
3610  OUTPUT 722;"T3"
3620  ENTER 722;Vpho0
3630  PRINT "Vpho0=";Vpho0
3640  INPUT "READING OK? (Y/N)",Zz$
3650  IF Zz$="N" THEN GOTO Pho0cal
3660 Phomaxcal:  !
3670  PRINT USING "@"
3680  PRINT "****CALIBRATION****"
3690  PRINT "APPLY THE MAXIMUM PRESSURE USING DEAD-WEIGHT TESTER"
3700  INPUT "ENTER THE MAXIMUM PRESSURE IN psig",Phomax
3710  DISP "HIT CONTINUE WHEN READY"
3720  PAUSE
3730  REMOTE 709
3740  OUTPUT 709;"AC21"
3750  OUTPUT 722;"T3"
3760  ENTER 722;Vphomax
3770  PRINT "Vphomax=";Vphomax,"Phomax=";Phomax
3780  Kpho=Phomax/(Vphomax-Vpho0)
3790  PRINT "Kpho=";Kpho
3800  BEEP
3810  INPUT "READING OK? (Y/N)",Zz$
3820  IF Zz$="N" THEN GOTO Phomaxcal
3830  IF Avg=1 THEN GOTO Avgcal
3840 Endcal:                    !
3850 Fincal: !
3860  PRINT USING "@"
3870  PRINT "THIS ENDS THE CALIBRATIONS"
3880  !*************************************************************************
3890  !(3) PRE-RUN INPUTS, FLOW RATE CHECKS AND NOZZLE CALCULATIONS
3900  !*************************************************************************
3910  !*************************************************************************
3920  ! A. FLOW RATE SET-UPS AND CHECKS
3930  !*************************************************************************
3940  PRINT USING "@"
3950  INPUT "DO YOU WANT TO PRESET THE AIR FLOW RATE?(Y/N)",Zz$
3960  IF Zz$="N" THEN GOTO Paskip
3970  PRINT "SET THE DESIRED VALUE OF Pa(psig) USING THE HAND LOADER ,PRESSURE G
AGE"
3980  PRINT USING "3/"
3990  PRINT "THE HAND LOADER SHOULD BE 20 PSIG MORE THAN DESIRED PRESSURE"
4000 Paset: !
4010  PRINT USING "3/"
4020  PRINT "MANUALLY INITIATE AIR FLOW BY TURNING 'MAIN AIR' ON CONTROL PANEL"
4030   PRINT USING "2/"
4040   DISP "HIT CONTINUE WHEN READY"
4050   PAUSE
4060   WAIT 3
4070   OUTPUT 709,"AC34"
4080   OUTPUT 722;"T3"
4090   ENTER 722;Vpa
4100   OUTPUT 709;"AC60"
4110   OUTPUT 722;"T3"
4120   ENTER 722;Vta
4130   OUTPUT 709;"AC61"
4140   OUTPUT 722;"T3"
4150   ENTER 722;Vti
4160   BEEP
4170   PRINT USING "@"
4180   PRINT "TURN OFF 'MAIN AIR'"
4190   DISP "HIT CONTINUE TO PROCEED"
4200   PAUSE
4210   Pa=(Vpa-Vpa0)*Kpa+Pbar
4220   Volts=Vta
4230   [illegible]
```

```
4230    GOSUB Tcalc
4240    Ta=T
4250    Volts=Vii
4260    GOSUB Tcalc
4270    Tcin=T
4280    Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
4290    Bpair=Kmair*Cdair*Pa*.7854*(Dbpchoke^2)/(Ta^.5)
4300    PRINT USING "@"
4310    PRINT USING "5A,2X,DDD.DDDD";"Mair=";Mair
4320    PRINT USING "14A,DDD.DDD";"Mair DESIRED=";Maird
4330    Ratio=Mair/Maird
4340    PRINT USING "20A,D.DDD,2X,3A,1X,DDDD.D,1A,3X,3A";"Mair/DESIRED Mair=";Rat
io,"Ta=";Ta,"R"
4350    PRINT USING "6A,2X,DDD.DDDD";"BPair=";Bpair
4360    Pg=Pa-Pbar
4370    PRINT USING "4A,DDDD.D,6A";"Pa =";Pg;"  Psig"
4380    PRINT USING "4A,DDDD.D,3A";"Ta =";Ta;"  R"
4390    INPUT "IS AIR FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
4400    IF Xx$="Y" THEN GOTO Prerun
4410    Panew=(Pa*Maird/Mair)-Pbar
4420    PRINT "RESET Pa TO";Panew;"Psig"
4430    DISP "HIT CONTINUE AFTER RESET OF Pa"
4440    PAUSE
4450    GOTO Paset
4460 Prerun:      !
4470    INPUT "DO YOU WANT PRINTOUT OF PRE-RUN DATA?(Y/N)",Xx$
4480    IF Xx$="Y" THEN GOTO Preprint
4490    GOTO Skipprint
4500 Preprint:   !
4510            PRINTER IS 701
4520    PRINT "                    **** PRE-RUN DATA, USING AIR ONLY    ****"
4530    PRINT ""
4540    PRINT "DATE:     ";Date$
4550    PRINT USING "3A,DDDD.D,6A";"Pa=";Pa,"  Psia"
4560   !PRINT USING "3A,DDD.D,3A";"Tcin=",Tcin,"  R"
4570    PRINT USING "5A,D.DDDD,11A";"Mair=";Mair,"  (Lbm/sec)"
4580    PRINT USING "5A,D.DDDD,11A";"BPair=";Bpair," (lbm/sec)"
4590    PRINTER IS 1
4600 Skipprint: !
4610    DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
4620    PAUSE
4630 Paskip:   !
4640            IF Ht=0 THEN GOTO Phfskip
4650    PRINT USING "@"
4660    INPUT "DO YOU WANT TO PRESET THE HEATER FUEL FLOW RATE? (Y/N)",Zz$
4670    IF Zz$="N" THEN GOTO Phfskip
4680 !************************************************************************
4690   PRINT "SET THE DESIRED VALUE OF Phf USING THE HAND LOADER/PRESSURE GAGE"
4700 !************************************************************************
4710   DISP "HIT CONTINUE WHEN READY"
4720   PAUSE
4730 Phfset:!
4740    PRINT USING "@"
4750    PRINT "MANUALLY TURN ON AIR 'HEATER FUEL' SWITCH"
4760    DISP " HIT CONTINUE TO PROCEED"
4770    PAUSE
4780    OUTPUT 709;"AC22"
4790    OUTPUT 722;"T3"
4800    ENTER 722;Vphf
4810    OUTPUT 709;"AC65"
4820    OUTPUT 722;"T3"
4830    ENTER 722;Vthf
4840   !CLEAR 709
4850    PRINT "MANUALLY TURN OFF AIR 'HEATER FUEL' SWITCH"
4860    BEEP
4870    DISP "HIT CONTINUE TO PROCEED"
4880    PAUSE
4890    Phf=(Vphf-Vphf0)*Kphf+Pbar
4900    Volts=Vthf
4910    GOSUB Tcalc
4920    Thf=T
4930    Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
```

```
4940   PRINT USING "@"
4950   PRINT USING "4A,DD.DDDDD";"Mhf=";Mhf
4960   PRINT USING "12A,DD.DDDDD";"Mhf DESIRED=";Mhfd
4970   Ratio=Mhf/Mhfd
4980   PRINT USING "18A,D.DDD,2X,4A,DDDD.DD,1A";"Mhf/ Mhf DESIRED=";Ratio,"Thf="
;Thf,"R"
4990   Pg=Phf-Pbar
5000   PRINT USING "5A,DDDD.DDD,4A,3X,4A,DDDD.DD,1A,4A,DDDD.DD,1A";"Phf= ";Pg;"P
sig","Thf=";Thf;"R"
5010   INPUT "IS HEATER FUEL FLOW RATE ACCURATE ENOUGH? (Y/N)",Xx$
5020   IF Xx$="Y" THEN GOTO Phffin
5030   Phfnew=(Phf*Mhfd/Mhf)-Pbar
5040   PRINT USING "13A,DDDD.DD,4A";"RESET Phf TO";Phfnew;"Psig"
5050   DISP "HIT CONTINUE AFTER RESET OF Phf"
5060   PAUSE
5070   GOTO Phfset
5080 Phffin:!
5090     DISP "HIT CONTINUE TO PROCEED TO NEXT FLOW RATE SET UP"
5100     PAUSE
5110 Phfskip:    !
5120     PRINT USING "@"
5130   INPUT "DO YOU WANT TO PRESET THE HEATER OXYGEN FLOW RATE?(Y/N)",Zz$
5140    IF Zz$="N" THEN GOTO Phoskip
5150    !*******************************************************************
5160   PRINT "SET THE DESIRED VALUE OF Pho USING THE HAND LOADER/PRESSURE GAGE"
5170    !*******************************************************************
5180 Phoset:!
5190         PRINT "MANUALLY TURN ON AIR 'HEATER OXYGEN' SWITCH"
5200         DISP "HIT CONTINUE TO PROCEED"
5210         PAUSE
5220         OUTPUT 709;"AC21"
5230         OUTPUT 722;"T3"
5240         ENTER 722;Vpho
5250         OUTPUT 709;"AC64"
5260         OUTPUT 722;"T3"
5270         ENTER 722;Vtho
5280         PRINT "MANUALLY TURN OFF AIR 'HEATER OXYGEN' SWITCH"
5290         BEEP
5300         DISP "HIT CONTINUE TO PROCEED"
5310         PAUSE
5320         Pho=(Vpho-Vpho0)*Kpho+Pbar
5330         Volts=Vtho
5340         GOSUB Tcalc
5350         Tho=T
5360         Mho=Kmho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
5370         PRINT USING "@"
5380        PRINT USING "4A,DD.DDDDD";"Mho=";Mho
5390        PRINT USING "18A,DD.DDDDD";"Mho DESIRED=";Mhod
5400         Ratio=Mho/Mhod
```

```
5410         Pg=Pho-Pbar
5420         PRINT USING "5A,DDDD.DD,1X,5A,5X,4A,DDDD.DD,1X,2A","Pho=";Pg;"Psig";
"Tho=";Tho;"R"
5430        INPUT "IS THE HEATER OXYGEN FLOW RATE ENOUGH? (Y/N)?",Xx$
5440         IF Xx$="Y" THEN GOTO Phoskip
5450         Phonew=(PhoXMhod/Mho)-Pbar
5460        PRINT USING "14A,DDDD.DD,1X,4A";"RESET Pho  TO ";Phonew;"Psig"
5470        DISP "HIT CONTINUE AFTER RESET OF Pho"
5480         PAUSE
5490         GOTO Phoset
5500 Phoskip:    !
5510         PRINT "THIS COMPLETES PRE-RUN SET-UP"
5520 !*********************************************************************
5530 ! (4) THIS PORTION OF THE PROGRAM RUNS THE TEST AND COLLECTS THE DATA
5540 !*********************************************************************
5550 ! PRINT USING "@"
5560   DISP "SET TIMEDATE BY PRESSING K19 AND UPDATE, THEN EXECUTE, THEN HIT CON
TINUE"
5570   BEEP
5580   PAUSE
5590   PRINT USING "@"
5600 Rpt:  !
5610         PRINTER IS 1
5620   ! THE FOLLOWING PROGRAMS THE 3456 DVM
5630   ASSIGN @Scanner TO 709
5640   ASSIGN @Svm TO 722
5650   CLEAR @Svm
5660   OPTION BASE 1
5670   DIM Press(10,5)
5680   DIM Temp(10,5)
5690   DIM Avgtemp(10,3)
5700   CLEAR @Svm
5710   OUTPUT @Svm;"L1Z1D0S0F1R3O3TD1STNP0FL01STIS01T401G#1"
5720   DISP "HIT CONTINUE FOR HOT RUN DATA"
5730   BEEP
5740   PAUSE
5750   DISP ""
5760   GOSUB Press
5770   GOSUB Tem
5780   IF Avg=1 THEN GOSUB Avg
5790   GOTO Shutdown
5800   !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
5810 Press:          !
5820  PRINT USING "@"
5830  PRINT USING "10/"
5840  PRINT "     ************  COLLECTING PRESSURE   ************"
5850  PRINT ""
5860  PRINT "     ************  COLLECTING PRESSURE   ************"
5870     OUTPUT @Scanner;"AC21AF21AL25AE2"
5880     WAIT .2
5890     OUTPUT @Svm;"50STNT3"
5900     ENTER @Svm USING "#,K";Press(X)
5910      !                                          SUBROUTINE Press
5920    OUTPUT @Svm;"1STNT4"
5930    RETURN
5940    !!!!!!!!!!!!!!!!!!!!!!!!!!!!
```

```
5940     !************************************************************************
5950 Aug:     !  TEMPERATURE COLLECTING ROUTINE FOR AUGMENTOR TUBE
5960    PRINT "***  COLLECTING AUGMENTOR TEMPERATURES  ****"
5990       OUTPUT @Scanner;"AC66AF66AL60AE2"
5991       OUTPUT @Svm;"30STNR2T3"
5992       WAIT .2
6000       ENTER @Svm USING "#,K";Augtemp(*)
6010       OUTPUT @Svm;"R31STNT4"
6020       RETURN
6030     !************************************************************************
6040 Tem:        !
6050      PRINT " *****COLLECTING TEMPERATURES ******"
6060       OUTPUT @Svm;"60STNR2"
6070       OUTPUT @Scanner;"AC60AF60AL65AE2"
6080       WAIT .2
6090       OUTPUT @Svm;"60STNR2T3"
6100       ENTER @Svm USING "#,K";Temp(*)
6110     OUTPUT @Svm;"1STNR3T4"
6120     RETURN
6130     !************************************************************************
6140 Shutdown:  !
6150              PRINT USING "@"
6160              PRINT " TEST COMPLETE: TURN OFF MAIN-AIR, HEATER GASES "
6170 !************************************************************************
6180 !*  (E) POST-RUN OPERATION, DATA REDUCTION AND SHUTDOWN
6190 !************************************************************************
6200              DISP "HIT CONTINUE TO PROCEED TO DATA REDUCTION"
6210              BEEP
6220              PAUSE
```

```
6230      PRINTER IS 701
6240  PRINT USING "3/"
6250  PRINT "                    ****  PRE-RUN INPUT   **** "
6260  PRINT USING "2/"
6270  PRINT USING "14A,9A,5X,14A,9A,5X,14A,9A";"Testno=";Testno$,"Date=";Date$,"
Fuelid=";Fuelid$
6280  PRINT USING "14A,9A";"Heaterfuel=";Heaterfuel$
6290  PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.DDD";"Dairchoke=";Dairchoke,"Dhfch
oke=";Dhfchoke
6300  PRINT USING "14A,DDDD.DDDD";"Dhtoxchoke=";Dhochoke
6310  PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.DDD,7X,14A,DDDD.DDD";"Cdair=";Cdair,
"Cdh=";Cdhf,"Cdho=";Cdho
6320  PRINT USING "14A,DDDD.DDD,5X,14A,DDDD.DDD,5X,14A,DDDD.DDD";"Gammahf=";Gamm
ahf
6330  PRINT USING "14A,DDDD.DD,5X,14A,DDDD.DD,5X,14A,DDDD.DD";"Rhf=";Rhf
6340  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Khf=";Khf
6350  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD";"Kmho=";Kmho,"Kmair=";Kmair
6360  PRINT USING "14A,DDDD.DDD,6X,14A,DDDD.D";"Maird=";Maird,"Icind=";Icind
6370  PRINT USING "14A,DDDD.DDDD,5X,14A,DDDD.DDDD,5X,14A,DDDD.DDDD,4X,14A,DDDD.D
DDD";"Mhfd=";Mhfd,"Mhod=";Mhod,"Mfueld=";Mfueld
6380  PRINT USING "14A,DDDDD.DDDD,5X,14A,DDDDD.DDDD,5X,14A,DDDDD.DDDD,5X,14A,DDD
D.DDDD";"Kpa=";Kpa;"Vpa0=";Vpa0;"Kpc=";Kpc;"Vpc0=";Vpc0
6390  PRINT USING "3/"
6400  PRINT ""
6410  PRINT USING "35X,28A";"****  DATA  EXTRACTED   ****"
6420  PRINT ""
6430  PRINT USING "120A";"FUEL FLOW RATE IN Gal/min, GAS FLOW RATES IN Lbm/sec,
PRESSURE IN Psia, TEMPERATURES IN R"
6440      PRINT USING "5A,6X,6A,5X,6A,7X,6A,9X,6(7A,5X)";"Count","Mair","Mhoair
","Mfuel","f","Mhf","Mho","Phf","Pho","Fc"
6450    FOR I=1 TO In
```

```
[illegible]
6460      Vpa=Press(J,4)
6470      Pa=(Vpa-Vpa0)*Kpa+Pbar
6480      Vpc=Press(J,3)
6490      Pc=(Vpc-Vpc0)*Kpc+Pbar
6500       Vmfuel=Press(J,5)
6510       Mfuel=Vmfuel*Kmfuel
6520      IF Ht=1 THEN
6530       Vphf=Press(J,2)
6540       Phf=(Vphf-Vphf0)*Kphf+Pbar
6550        Vpho=Press(J,1)
6560       Pho=(Vpho-Vpho0)*Kpho+Pbar
6570       END IF
6580       Volts=Temp(J,1)
6590       GOSUB Tcalc
6600       Ta=T
6610      IF Ht=1 THEN
6620       Volts=Temp(J,5)
6630       GOSUB Tcalc
6640       Tho=T
6650       Volts=Temp(J,6)
6660       GOSUB Tcalc
6670       Thf=T
6680      END IF
6690      !
6700    Mair=Kmair*Cdair*Pa*.7854*(Dairchoke^2)/(Ta^.5)
6710    Bpair=Kmair*Cdair*Pa*.7854*(Dbpchoke^2)/(Ta^.5)
6720    F=.108*Mfuel/Mair
6730    IF Ht=0. THEN GOTO Jump
6740    IF Phf<=(Pc*2) THEN Mhf=0.
6750    IF Pho<=(Pc*2) THEN Mho=0.
6760    Mhf=Kmhf*Cdhf*Phf*.7854*(Dhfchoke^2)/(Thf^.5)
6770    Mho=Kmho*Cdho*Pho*.7854*(Dhochoke^2)/(Tho^.5)
6780 Jump: !
6790          IF Ht=0. THEN
6800             Phf=0
6810             Pho=0
6820             Mhf=0
6830             Mho=0
6840             END IF
6850    ! THE VALUES BELOW ARE DEFAULT VALUES TO PREVENT PRINTER ERRORS
6860    IF Mair<.0001 THEN Mair=.0001
6870    IF Bpair<.0001 THEN Bpair=.0001
6880    IF Mfuel<.0001 THEN Mfuel=.0001
6890    IF F<.0001 THEN F=.0001
6900    IF Mhf<.0001 THEN Mhf=.0001
6910    IF Mho<.0001 THEN Mho=.0001
6920    IF Phf<.0001 THEN Phf=.0001
6930    IF Pho<.0001 THEN Pho=.0001
6940    IF Pc<.0001 THEN Pc=.0001
6950    IF Mair>2000. THEN Mair=2000.
6960    IF Bpair>2000. THEN Bpair=2000.
6970    IF Mfuel>2000. THEN Mfuel=2000.
6980    IF F>2000. THEN F=2000.
6990    IF Mhf>2000. THEN Mhf=2000.
7000    IF Mho>2000. THEN Mhf=2000.
7010    IF Phf>2000. THEN Phf=2000.
7020    IF Pho>2000. THEN Pho=2000.
7030    IF Pc>2000. THEN Pc=2000.
7040    PRINT USING "DDD,3X,MD.DDDE  ,3X,MD.DDDE  ,3X,MD.DDDE  ,3X,3(MD.DDDE  ,3X
),3(MD.DDE  ,3X),1X";J,Mair,Bpair,Mfuel,F,Mhf,Mho,Phf,Pho,Pc
7050    NEXT J
```

```
7060      PRINT " "
7070      PRINT USING "5A,5X,7(7A,7X)";"Count","Ta","Tcin","Tex1","Tex2","Tavgup
","Tavgd1","Tavgd2"
7080    FOR J=1 TO 10
7090      Volts=Temp(J,1)
7100        GOSUB Tcalc
7110        Ta=T
7120      Volts=Temp(J,2)
7130        GOSUB Tcalc
7140        Tcin=T
7150      Volts=Temp(J,3)
7160        GOSUB Tcalc
7170        Tex1=T
7180      Volts=Temp(J,4)
7190        GOSUB Tcalc
7200        Tex2=T
7210      Volts=Avgtemp(J,1)
7220        GOSUB Tcalc
7230        Tavgup=T
7240      Volts=Avgtemp(J,2)
7250        GOSUB Tcalc
7260        Tavgd1=T
7270      Volts=Avgtemp(J,3)
7280        GOSUB Tcalc
7290        Tavgd2=T
7300     IF Ta<100. THEN Ta=100.
7310     IF Tcin<100. THEN Tcin=100.
7320     IF Tex1<100. THEN Tex1=100.
7330     IF Tex2<100. THEN Tex2=100.
7340     IF Tavgup<100. THEN Tavgup=100.
7350     IF Tavgd1<100. THEN Tavgd1=100.
7360     IF Tavgd2<100. THEN Tavgd2=100.
7370     IF Ta>4000. THEN Ta=4000.
7380     IF Tcin>4000. THEN Tcin=4000.
7390     IF Tex1>4000. THEN Tex1=4000.
7400     IF Tex2>4000. THEN Tex2=4000.
7410     IF Tavgup>4000. THEN Tavgup=4000.
7420     IF Tavgd1>4000. THEN Tavgd1=4000.
7430     IF Tavgd2>4000. THEN Tavgd2=4000.
7440      PRINT USING "DDD,3X,7(MDD.DDE,4X)";J,Ta,Tcin,Tex1,Tex2,Tavgup,Tavgd1,T
avgd2
7450      NEXT J
7460    GOTO Finish
7470 Finish:     !
7480   PRINTER IS 1
7490   PRINT USING "@"
7500   PRINT "DATA OUTPUT IS COMPLETE"
7510   DISP "SECURE TEST CELL !!!"
7520   BEEP
7530   PAUSE
7540   END
```

APPENDIX B

Run Checklist

TEST CELL # 1

1. Ensure yellow and top blue air valves in the solid fuel ramjet cell are closed.

2. Open lower blue valve (opens air line to Test Cell #2 or T-63).

** Note ** At least one valve should be open at all times from the main air line to ensure an air vent in the event of component failure.

NITROGEN BOTTLE ROOM

1. Fully open the control room nitrogen bottle. Ensure that there is at least 1000 psi.

2. Fully open actuator nitrogen bottle. Ensure that there is at least 500 psi available.

CONTROL ROOM

1. Ensure AC master switch is on and the red covered main air switch is closed on the solid fuel ramjet control panel.

2. Ensure the air flow set pressure is zero.

3. Ensure the T-63 combustion chamber safety thermocouple is installed and operating.

4. Ensure the fuel tank set pressure (gauge on panel) is less than 500 psi.

FUEL STORAGE ROOM

1. Open nitrogen bottle valve (need at least 400 psi more pressure available in the bottle than the desired fuel line/tank pressure, or 900 psi minimum).

2. Adjust hand loader to read 700 psi.

3. Slowly open the nitrogen gas supply valve located behind the fuel tank near the wall.

4. Slowly open the fuel line valve from the bottom of the tank.

OUTSIDE/CONTROL ROOM

1. Open main air plug valve to full open (minimum of 2500 psi required for a run).

2. Ensure all thermocouples are turned on (if required) and pressure transducers and tubing are secure at the test stand.

3. The heated sample line temperature control box should be set to 275 deg.F and the gas analyzers in the control room should be up and operating. The three main power switches for the electronic equipment racks should be ON.

4. Load and run the "T63NOX" computer program on the HP microcomputer. The pressure transducers should now be calibrated if not already done. Enter the appropriate zeros and constants in the program.

5. Set the main air pressure to 600 psi using the hand loader.

6. Set the fuel pressure to 500 psi using the hand loader.

7. Go though the flow rate set procedures in accordance with the computer program.

8. Ensure the printer is "on-line".

9. Check for personnel near the cell and for golfers. Activate the exterior warning horn an check main air flow rate when cued by the computer.

10. Check that safety key No. 3 is inserted and enabled.

11. Turn on the siren.

12. Start strip chart recorder and mark zero/ambient conditions.

13. Signal for start of purge nitrogen.

14. Activate main air ON.

15. Simultaneously, activate the toggled engine ignitor and fuel switch. Check desired fuel flow rate (0.33 GPM). Watch for hot or wet start by visually observing exhaust smoke at rig and monitor the digital combustion chamber safety temperature readout (commence shutdown if temperature reaches 1380 deg. F).

16. When steady-state operation is reached, begin traversing the Kiel probe in the augmentor tube and obtain analyzer measurements.

17. While at steady operation collect data with the HP microcomputer and from the gas analysis equipment.

18. After data is gathered, switch fuel OFF. Leave main air on until engine and augmentor tube are ccol.

19. Turn main air CFF, record run time, and calculate fuel used during run. Update fuel board in fuel storage room.

20. Isolate fuel tank with valves and bleed excess fuel in lines with fuel switch activation.

21. Close main air valve outside.

22. Vent fuel tank from control panel if desired and close fuel tank nitrogen bottle.

23. Bleed remaining air heater and torch gases from lines and vent with remaining main air in lines. Back off pressure loaders to zero in the control room.

24. Secure analyzers, complete shutdown, and reduce data.

APPENDIX C

Gas Analyzer Checklist

Two Hours Prior

1. Turn on the Power to Model 900. It is not necessary to run any pumps at this time. When the heater has brought the unit up to temperature the temp cycle light will extinguish.

One Hour Prior

1. Turn on the Model 10AR power and ozone switch.
2. Turn on the Model 900 pump switch.
3. Plug in the vacuum pumps for the Model 10 and Model 900 (behind the cabinet on the floor).
4. Plug in the vacuum pump for the Model 900 mounted to the back of the unit.
5. Turn on the dilution gas to approximate one psi. This gas can be compressed ambient air.
6. Turn on O_2 for Model 10AR to 10 psi.
7. Expected readings on Model 900:

Chamber vacuum	23" Hg
Sample vacuum	10" Hg
Flow meter inside	1.8
Temp inside	175 deg F

Expected readings on Model 10:

Converter	650 deg C
Bypass	2.25 SCFH

Sample	5" Hg
Reaction chamber	29.5"Hg
O_2 press inside	2 psi

30 Minutes Prior

1. Turn on Model 48.

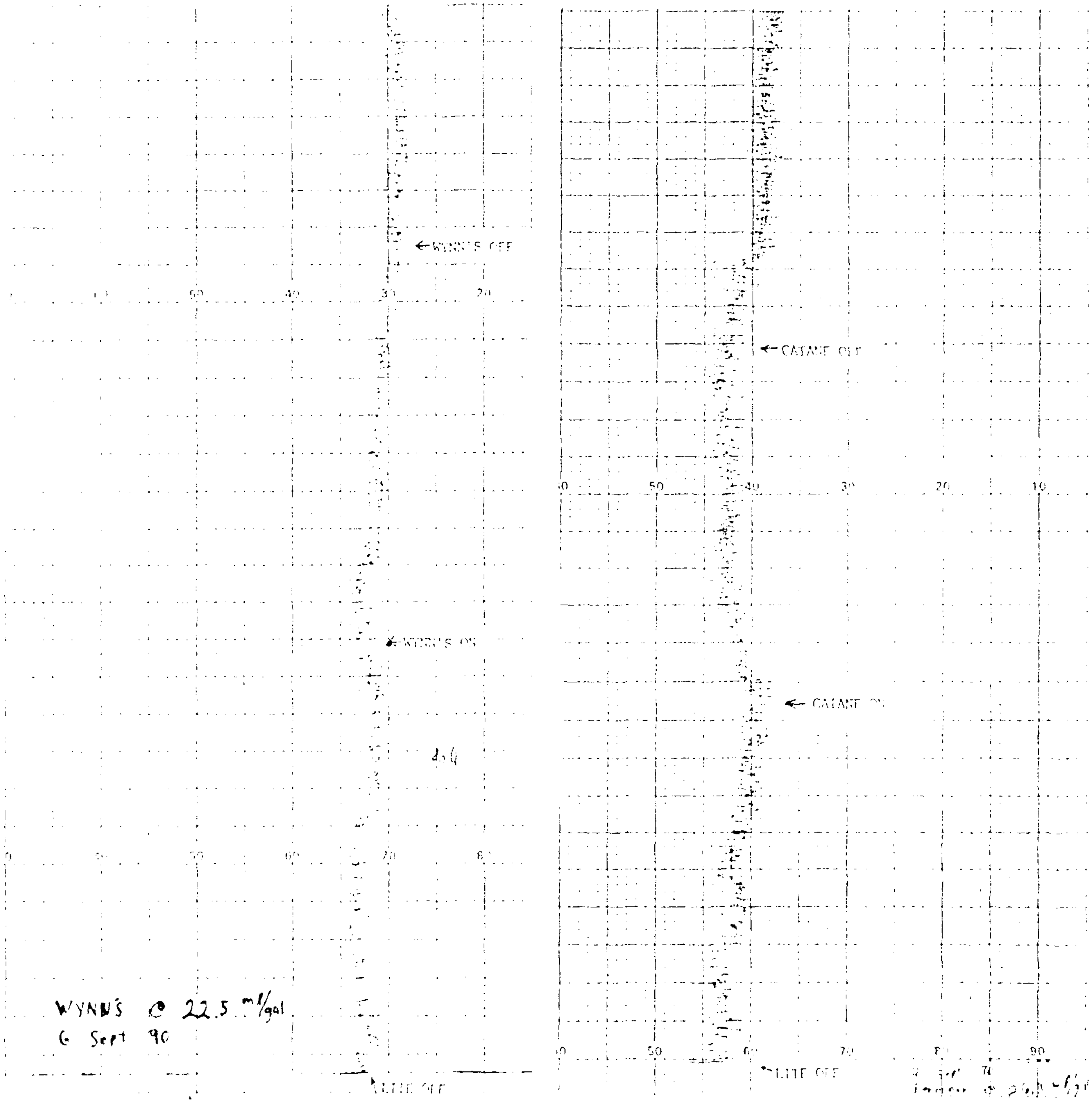
2. Turn on NO_x span gas to 3 psi an 0.8 SCFH and connect to span port of Model 900. Switch Model 900 to span. Note reading and adjust calibration to obtain exact concentration of span gas divided by 20.

3. Secure span gas and switch Model 900 back to sample and note Model 10 returns to zero.

4. Verify gas sample switch in test cell with air pressure.

APPENDIX D

Transmittance Data



APPENDIX E

TIMELINE FOR T-63 ADDITIVE TESTING

Min:Sec	Event
00:00	Purge air **ON**
00:02	Strip chart **ON**
00:05	Main air **ON**
00:07	Fuel **ON**
00:09	Ignitor **ON**
00:15	Engine light off (approx. 1200 F 0.33 GPM)
00:20	Check laser GO/NOGO Mark strip chart
00:25	Adjust view from IR camera if necessary
00:30	Operate at steady state no additive
01:00	Take hot run data HP and IR
01:45	Turn additive pumps **ON**
01:50	Mark strip chart
02:30	Take hot run data HP and IR
03:15	Turn additive pumps **OFF**
03:20	Mark strip chart
03:45	Take hot run data HP and IR
04:30	Secure fuel
04:35	Mark strip chart air only
04:55	Secure air
05:00	Secure purge/strip chart

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